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ACCELERATION SENSITIVITY COMPENSATION OF CRYSTAL RESONATORS,(U)

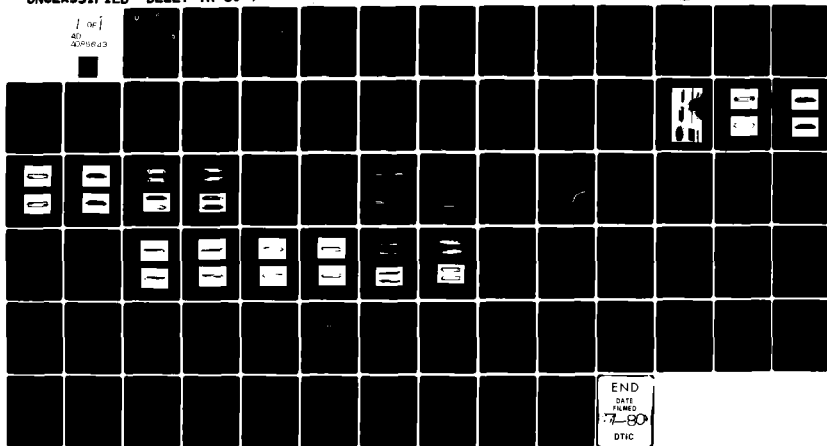
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RESEARCH AND DEVELOPMENT TECHNICAL REPORT

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**ACCELERATION SENSITIVITY COMPENSATION OF CRYSTAL  
RESONATORS**

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Arthur Ballato

ELECTRONICS TECHNOLOGY & DEVICES LABORATORY

March 1980

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report describes resonator configurations that are compensated for arbitrary directions of the acceleration field, and that require no additional electronics other than the oscillator circuitry normally used. This approach produces compensation with no changes in size, weight, and power, and applies to any crystal reference oscillator in any shock/vibration environment.		

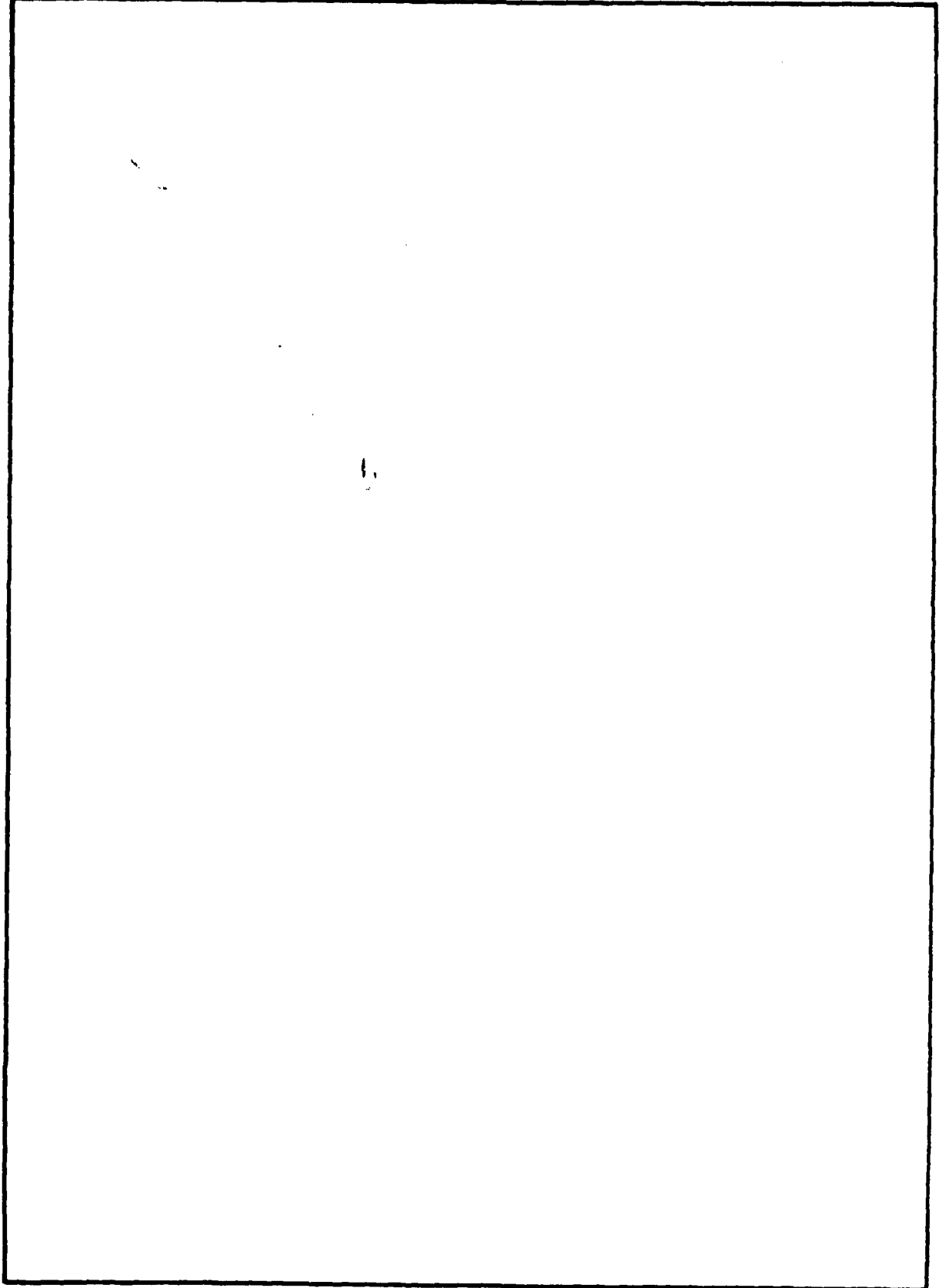
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## INTRODUCTION

For more than fifty years means have been sought to reduce environmentally induced frequency changes in crystal resonators. The search has been pressed through theoretical and experimental studies, and has covered a very broad range of causes.<sup>1-120\*</sup> Among the more recent effects receiving consideration are the force-frequency and acceleration-frequency. Frequency perturbations are produced in thickness mode crystal resonators by acceleration-induced body forces. These forces are distributed throughout the resonator volume and vary with the acceleration direction. For specific acceleration directions the effect can be sharply reduced by changing the points of application of the mounting supports. Even doubly rotated cuts may be accommodated, (although the mounting design varies with cut), and for some of these cuts the effect is further reduced below the value found for the AT cut. When the acceleration direction is known in advance, positioning the resonator with respect to this direction minimizes the problem.

In high shock and vibration environments such as in helicopters, tanks, and other vehicles, and the more moderate environments of manpack and aircraft collision avoidance system use, accelerations occur in arbitrary directions with ensuing large frequency shifts in the crystal resonance frequency. When the acceleration is arbitrarily oriented with respect to the resonator, no crystal cut and/or combination of mounting supports can by themselves produce cancellations of the frequency perturbations to the extent required, e.g., by secure communications systems. However, by taking advantage of the experimental fact that the resonance frequency shift changes sign with reversal of the acceleration direction and the fortunate happenstance that quartz occurs in right- and left-handed pairs, composite resonators of either discrete or stacked varieties may be fashioned having vastly decreased acceleration sensitivity, whatever the acceleration direction may be, with no concomitant degradation of any of the desirable resonator properties. The approach is applicable to doubly rotated crystals as well as singly, so that the additional nonlinear compensation of thermal transients, etc., that occurs for these cuts can be had along with acceleration hardening.

Figure 1 portrays an idealized frequency-time curve for a crystal resonator, depicting frequency changes due to a number of factors. This report is concerned with the episodes shown between times  $t_2$  and  $t_3$  and at  $t_4$  and  $t_7$ , namely, with the effects of vibration, shock, and crystal attitude ("tip-over"); these are subsumed under the name "acceleration".

## ACCELERATION EFFECTS

In the static force-frequency effect,<sup>1-31</sup> forces and moments acting on the peripheral boundary of a crystal resonator serve to produce frequency changes in the resonator. Accelerations of the crystal plate, on the other hand, produce distributed body forces throughout the resonator volume that are communicated at the crystal boundary to the mounting supports. The stress distribution within the crystal depends not only upon the mounting points, but also on the direction of the acceleration. In general, the static and dynamic effects will produce different states within the vibrator, and different frequency shifts.<sup>32-53</sup> Some applications of the effect to realize accelerometers

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\* See list of references beginning on page 63.

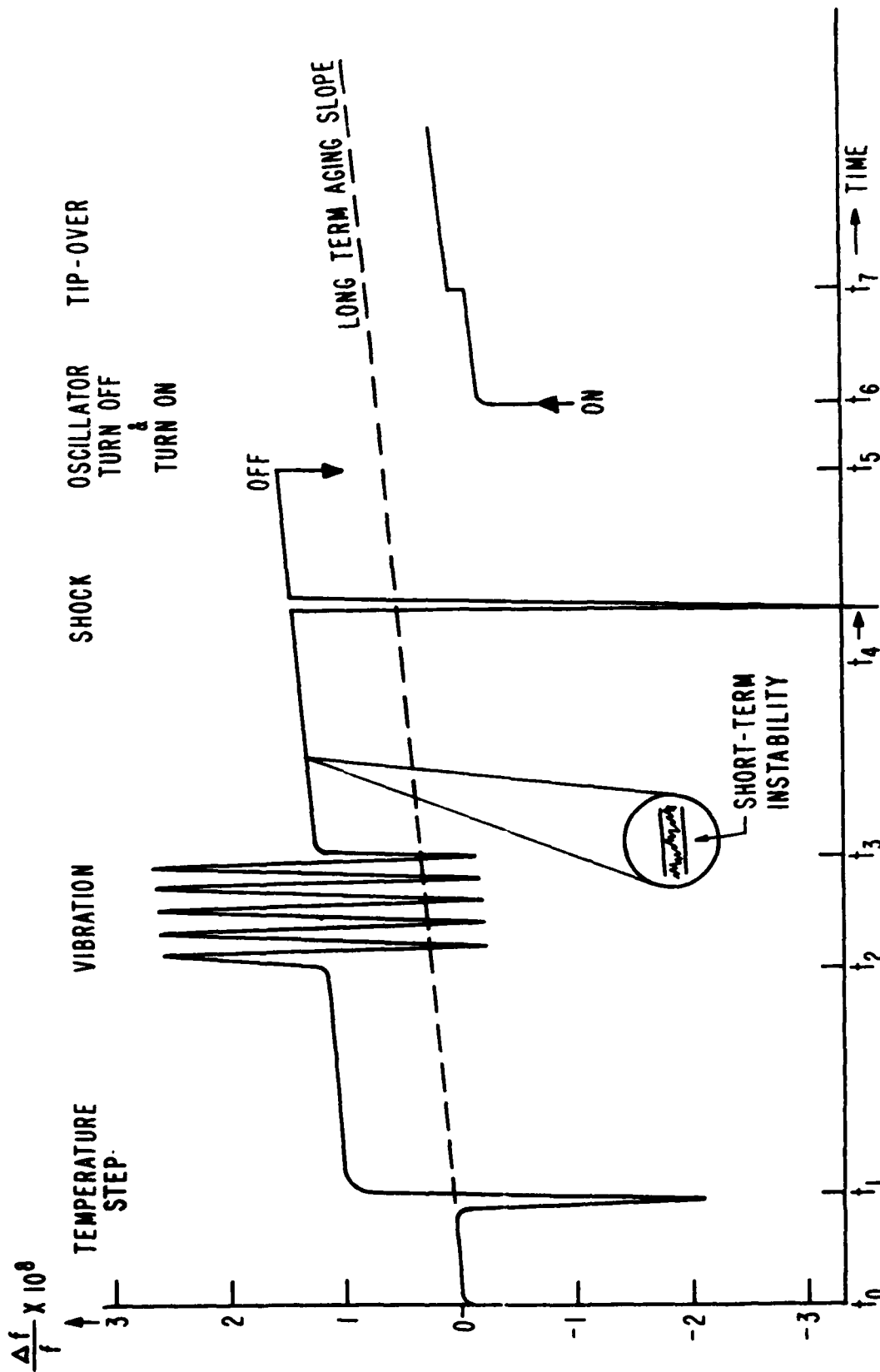


Figure 1. Frequency-time behavior of resonator.

have been made,<sup>36,42</sup> but much more often the effect is highly undesirable, and efforts to reduce the effect have continued for the past twenty years.<sup>32,52</sup>

Within the past five years the problem has become particularly acute, due to exacting requirements arising from the present and projected secure digital systems for communication, command, and control, and for navigation/position location. Fortunately, during this interval a number of advances have come about that in combination promise a significant reduction in the acceleration sensitivity of crystal resonators. One of these developments is the introduction of doubly rotated cuts.<sup>21-23,54</sup> Another is the use of new support configurations.<sup>53,55</sup> Additional developments will be detailed in ensuing sections.

Concurrent with these developments, a nonlinear theory has been fashioned by Lee and his co-workers that describes the force-frequency effect,<sup>15-20</sup> and acceleration effects in singly rotated, rotated-Y-cut quartz plates.<sup>40,46,49</sup> A plate theory has also been developed for doubly rotated quartz cuts.<sup>56</sup> Such a theory will provide a necessary understanding of the mounting support problem as applied to acceleration-compensated resonators.

#### ACCELERATION COMPENSATION

One of the most recent acceleration compensation schemes is the systems approach of Przyjemski.<sup>45,48,51</sup> In it, ancillary accelerometers sense the applied acceleration components along three orthogonal directions and this information is used to feed back a compensation signal to correct the crystal frequency. This arrangement provides improvements of a factor twenty or so over an uncompensated resonator, and works for arbitrary directions of applied acceleration.

Another acceleration compensation scheme is that of Gagnepain<sup>41,53,55</sup> and Walls. In this arrangement, two quartz vibrators are connected electrically in series, in the manner used long ago by Koga<sup>57,58</sup> to effect temperature compensation. Now, however, the crystals are oriented so that the axes along which the acceleration-frequency effect is greatest are antiparallel in pairs. According to the measurements of Valdois<sup>37-39</sup> for AT cut discs supported along the Z' axis, the directions of greatest acceleration sensitivity are for acceleration fields along the Y' axis, which coincides with the disc thickness, and for fields along the Z' axis. Because the sensitivity is least for X-directed fields, the discs are oriented so that the X axes of both discs are parallel, and the Y' and Z' axes are antiparallel. Then compensation is achieved for directions of acceleration lying in the plane normal to the common X axis. The experimental arrangement and results of Valdois are shown schematically in Figure 2.

A configuration alternative to that of Gagnepain and Walls was proposed by Vig,<sup>59</sup> wherein the two paired resonators are mated in the fashion of a two-layer stacked crystal filter,<sup>60-64</sup> as seen in Figure 3. In this case the angle between the X axes of both crystals would be zero. The acceleration-frequency behavior would be similar to that of the discrete configuration, but the stack would be more robust and occupy less room than two separate vibrators.

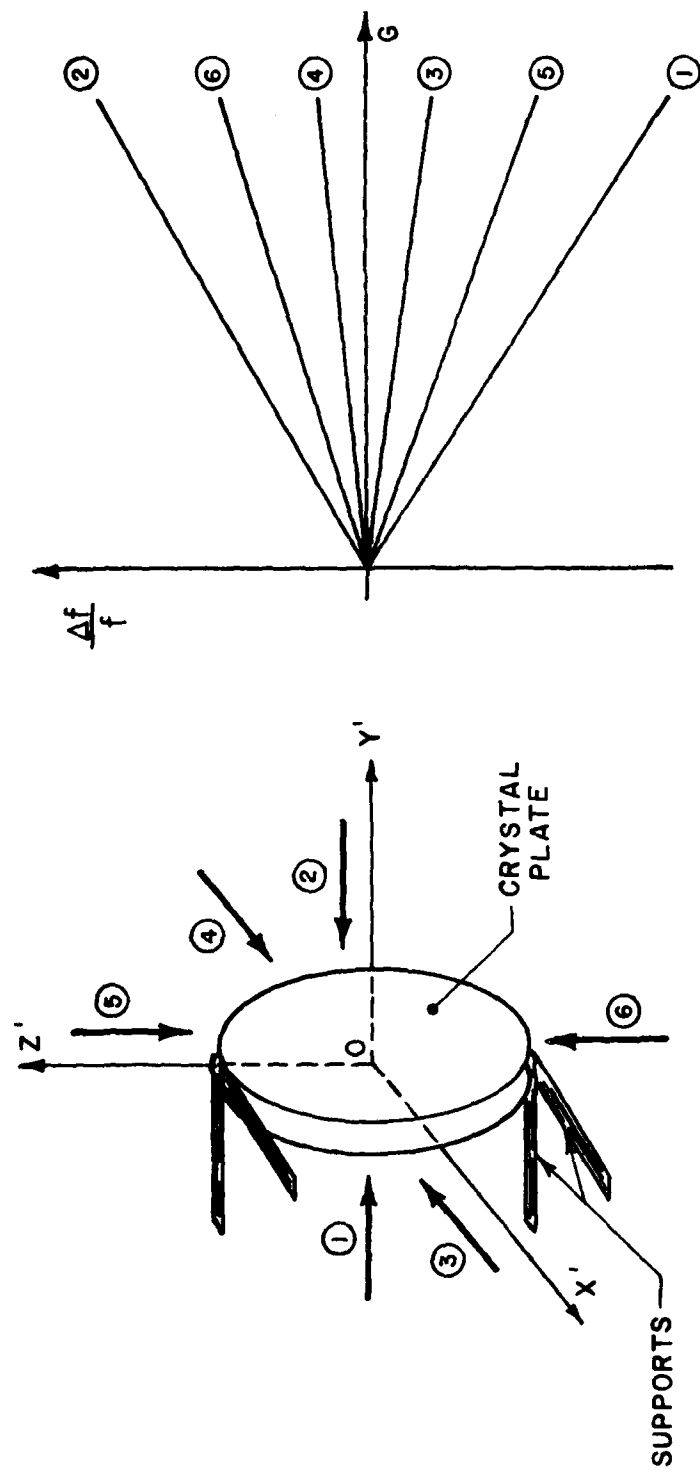


Figure 2. Frequency change versus acceleration.

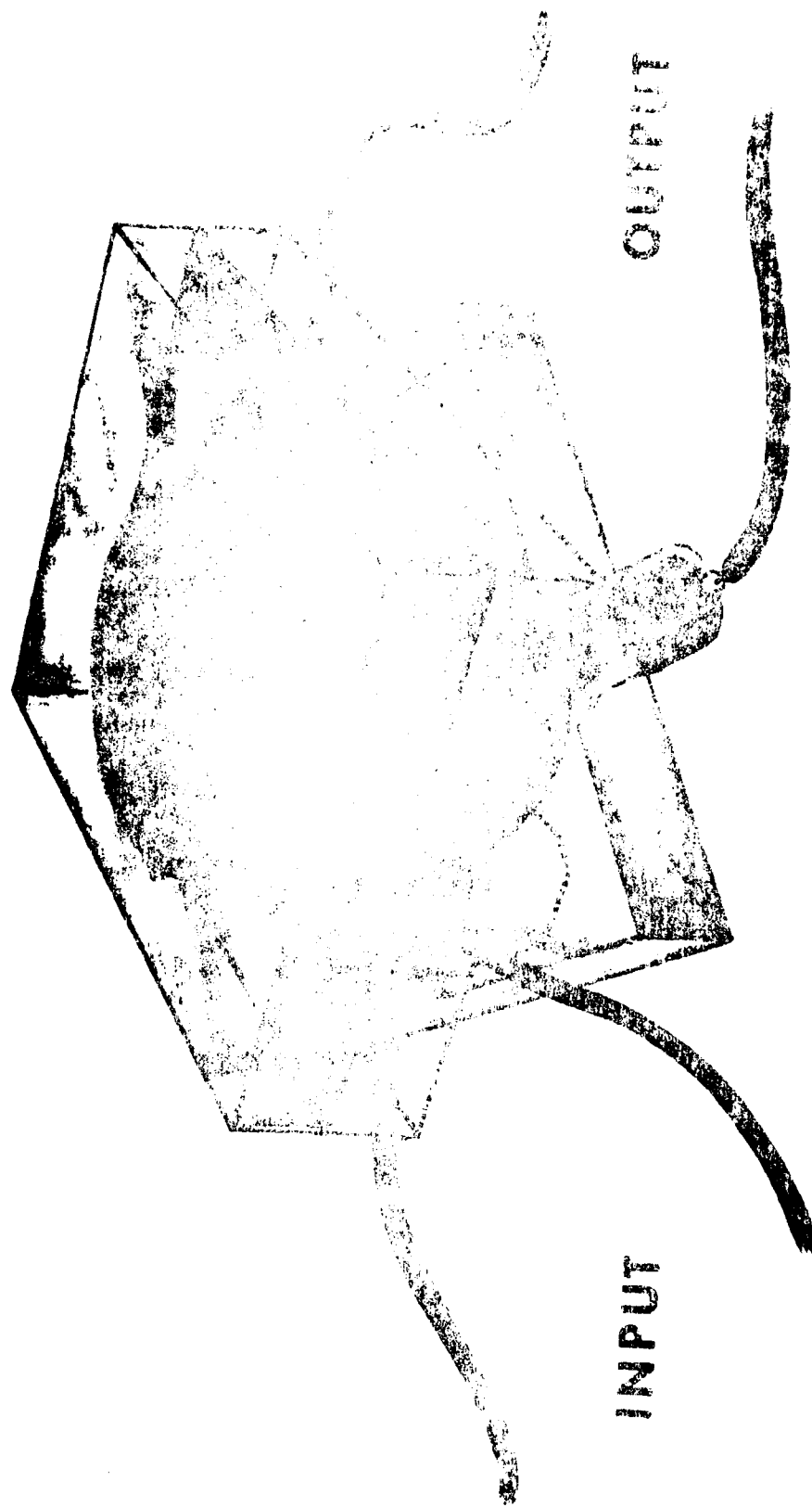


Figure 3. The stacked crystal filter.

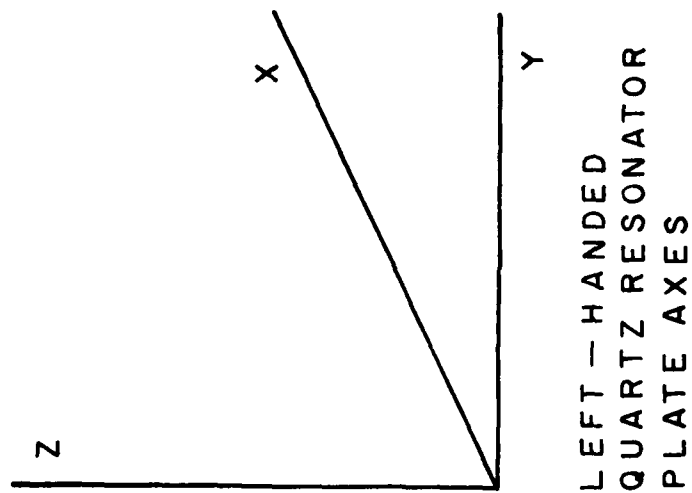
## ENANTIOMORPHOUS CRYSTALS

Two identical crystal resonators can only be manipulated so that an even number of their respective crystal axes are antiparallel. Reversal of an odd number requires an improper rotation. Fortunately, just such an operation is possible with quartz! The operation changes the handedness of the crystal. The existence of right- and left-handedness in a crystal is known as enantiomorphism. When two crystal resonators, identical except for their handedness, are used as a pair, they may be oriented with all three corresponding axes antiparallel as shown in Figure 4. Then, from the results shown in Figure 2, where the frequency change reverses sign with reversal of acceleration direction, paired resonators will suffer no frequency shift for any direction of the acceleration field. This statement holds for pairs configured as discrete vibrators, or as a composite stack. An example of the former, for series electrical connection, is seen in Figure 5.

Quartz is not the only enantiomorphous crystal. Any representative of the eleven crystal classes 1, 2, 222, 4, 422, 3, 32, 6, 622, 23 and 432 exhibits this property. These are the classes without a plane of symmetry. The enantiomorphs bear a mirror image relationship to each other; all are non-centrosymmetric, and hence (with the exception of class 432) are piezoelectric. There is at least one representative from each of the seven crystal systems. Berlinite,  $\alpha\text{-AsPO}_4$  (class 32) is enantiomorphous, lithium tantalate and lithium niobate (class 3m) are not. Additional details are given in Table 1.

Paired enantiomorphs of idealized crystals of quartz are given in Figures 6 to 10. In each case the left-hand type is on the left and the right-hand type is on the right. In the figures, and in the following, it will be convenient to use coordinate systems having the same chirality as the type of quartz: left for left-quartz, right for right-quartz. This convention was first proposed by Koga<sup>65</sup> in 1929 and adopted in a 1945 report by the IRE, following upon a paper by Cady and Van Dyke.<sup>66</sup> It is also used in Cady's book.<sup>67</sup> The 1949 IRE standard adopted a right-hand coordinate system for both forms<sup>68</sup> and the latest IEEE standard has continued the convention of its predecessor.<sup>69</sup> A recent paper by Donnay and Le Page<sup>70</sup> lucidly sets forth reasons for using two coordinate systems for enantiomorphs. Morphological enantiomorphism appears first to have been explicitly recognized by Louis Pasteur; the usual attribution is to Haüy who illustrated both types of quartz, but his writings do not show that he recognized the difference.<sup>71</sup> The question of priority is still very much an open one.<sup>72,73</sup>

The enantiomorphs discussed here correspond to what is called Brazil, or optical, twinning in natural quartz. The other category of twinning often present in natural quartz is Dauphiné, or electrical, twinning, where the two forms are rotated, with respect to each other, about the Z (or optic) axis so that the X axes are in opposite (antiparallel) directions, but the handedness is unaffected. Dauphiné twinning may be brought about relatively easily and involves small changes in atomic positions, whereas Brazil twinning requires the breaking of atomic bonds and a significant expenditure of energy.<sup>74,75</sup> The types of twins are shown in Figure 11. Yoda proposed the use of electrically and optically twinned quartz for crystal vibrators before cultured bars attained the degree of use that they enjoy today.<sup>76</sup>



LEFT - HANDED  
QUARTZ RESONATOR  
PLATE AXES

RIGHT - HANDED  
QUARTZ RESONATOR  
PLATE AXES

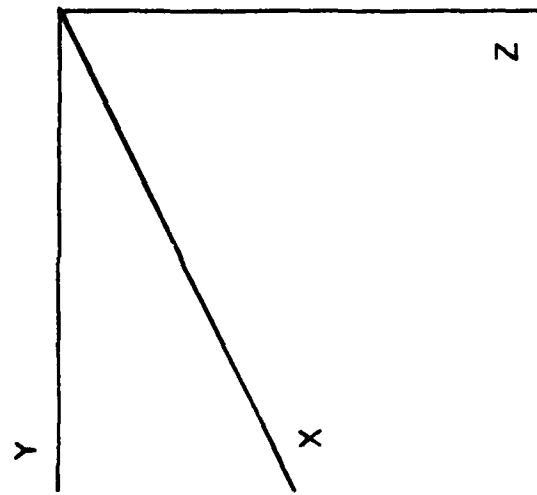


Figure 4. Paired coordinate systems.

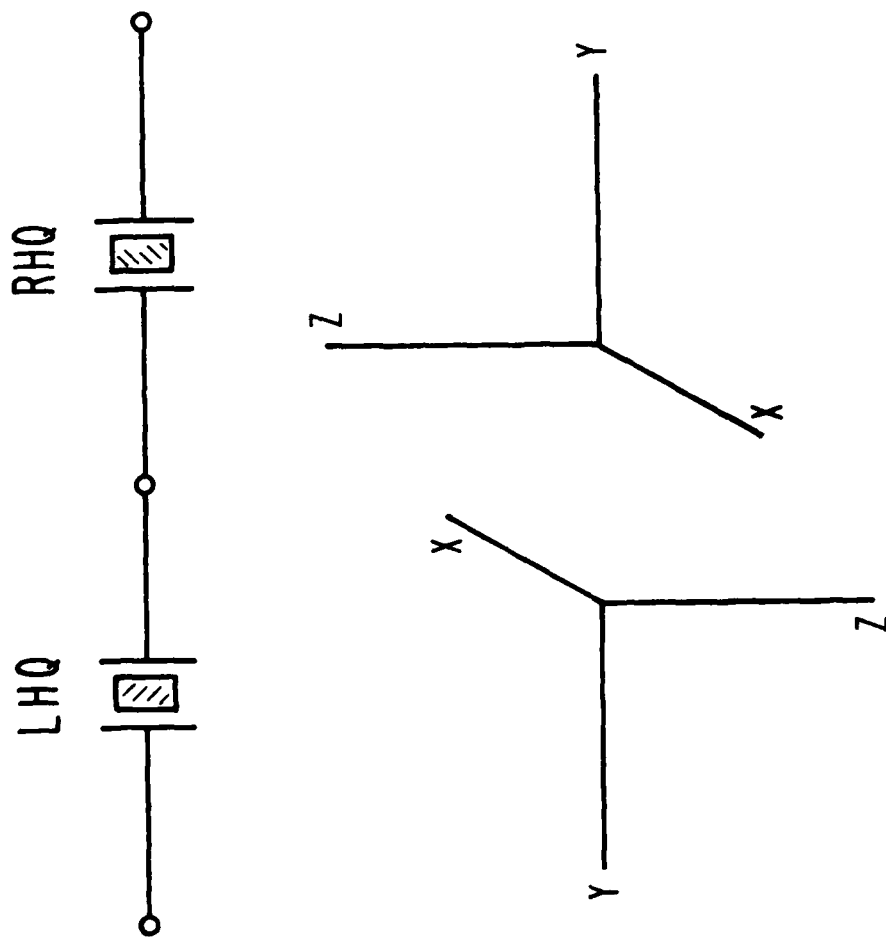


Figure 5. Series connected enantiomorphs.

TABLE 1. THE ELEVEN ENANTIMORPHOUS CRYSTAL CLASSES.

CRYSTAL SYSTEM	CLASS NUMBER	HERMANN-MAUGUIN SYMBOL	NUMBER OF ELASTIC COEFFICIENTS	
			SECOND ORDER	THIRD ORDER
I TRIGONAL	1	1	21	56
II MONOCLINIC	3	2	13	32
III ORTHORHOMBIC	6	222	9	20
IV a } TETRAGONAL	9	4	11/7	28/16
IV b }	12	422	9/6	20/12
V a } TRIGONAL	16	3	15/7	50/20
V b }	18	32	12/6	31/14
VI a } HEXAGONAL	21	6	9/5	28/12
VI b }	24	622	9/5	20/10
VII a } CUBIC	28	23	9/3	20/8
VII b }	30	432	9/3	20/6

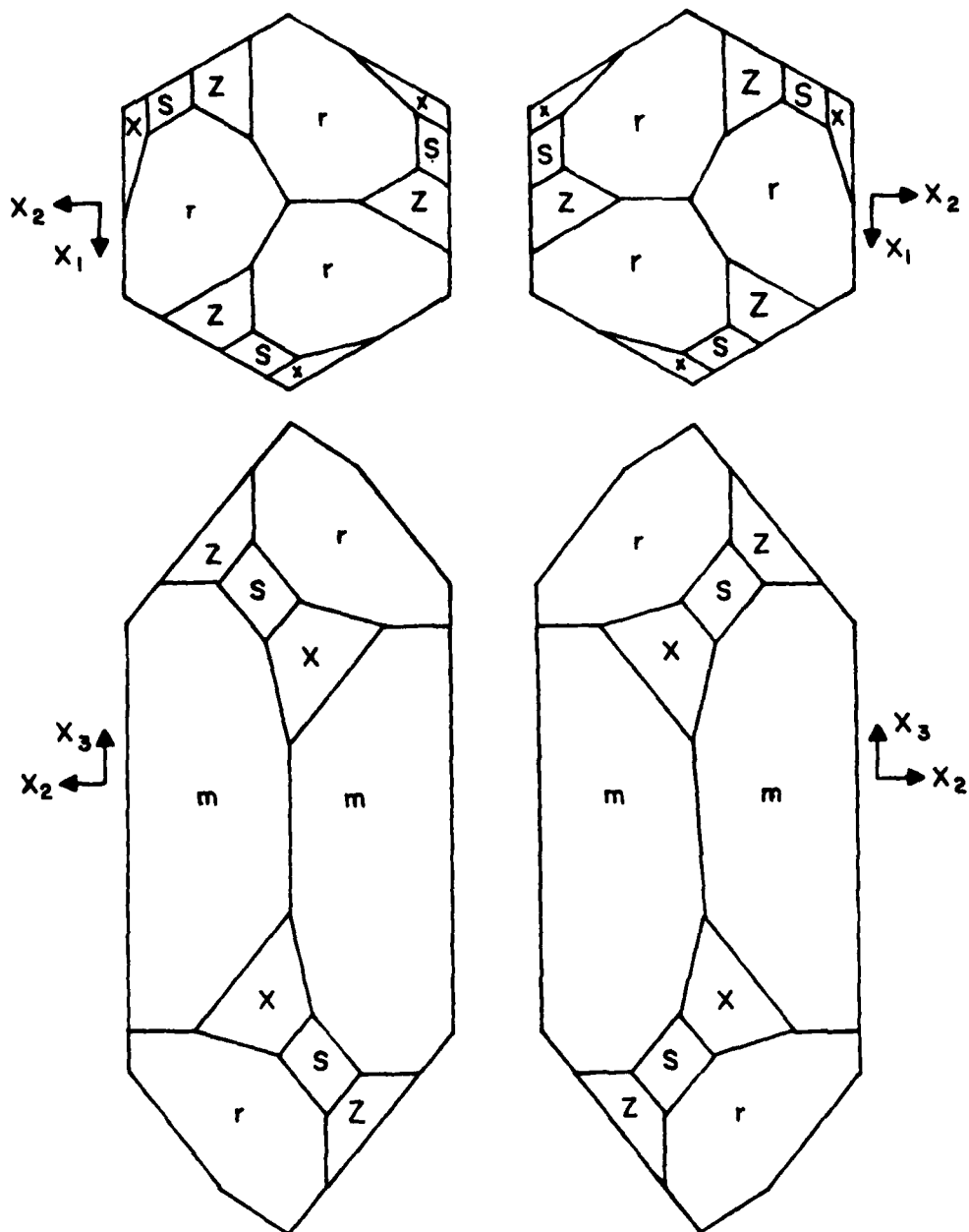


Figure 6. Quartz pairs. Top: looking down  $+X_3$ . Bottom: down  $+X_1$ .

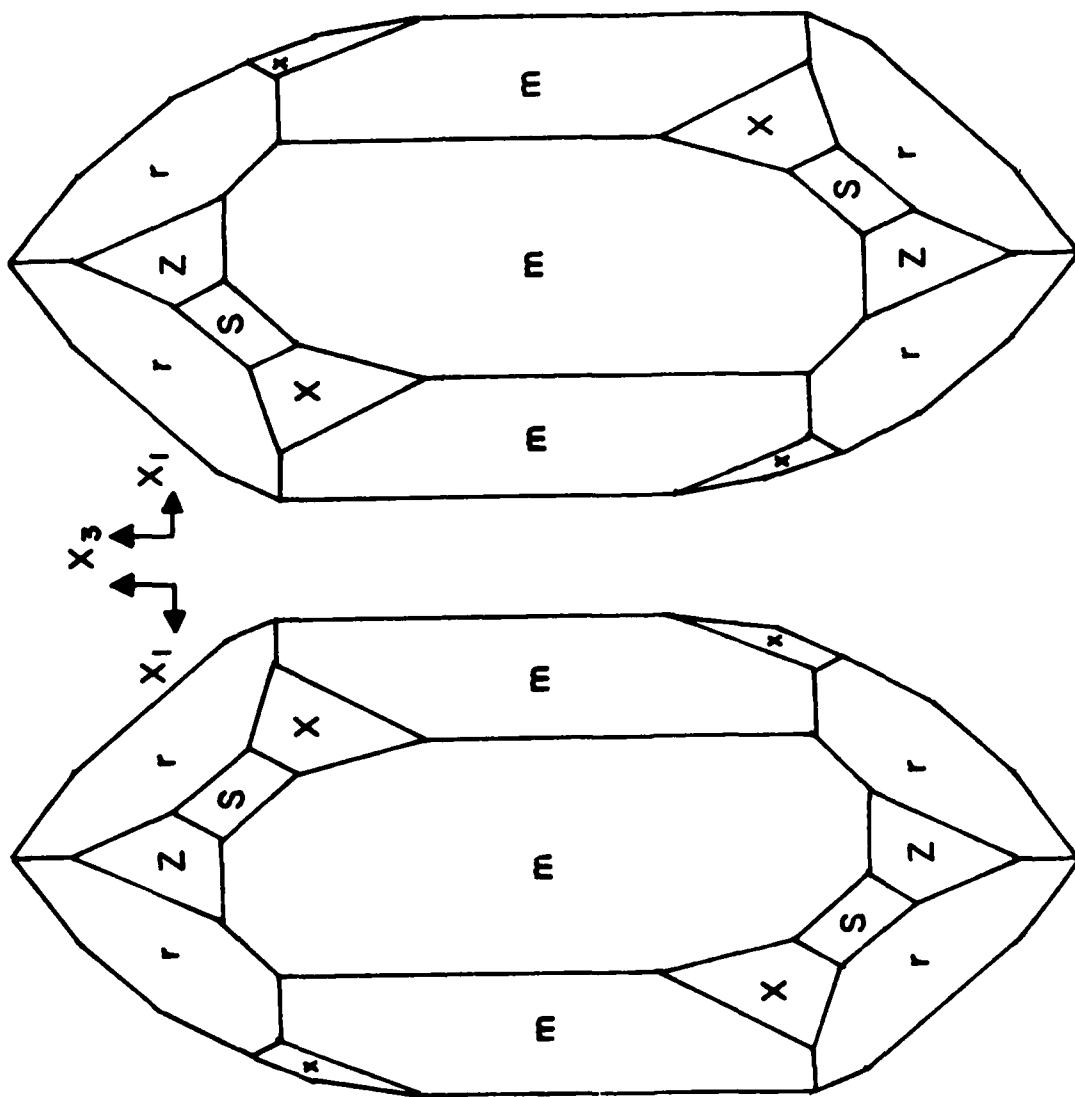


Figure 7. Quartz pairs. Looking down  $-X_2$ .

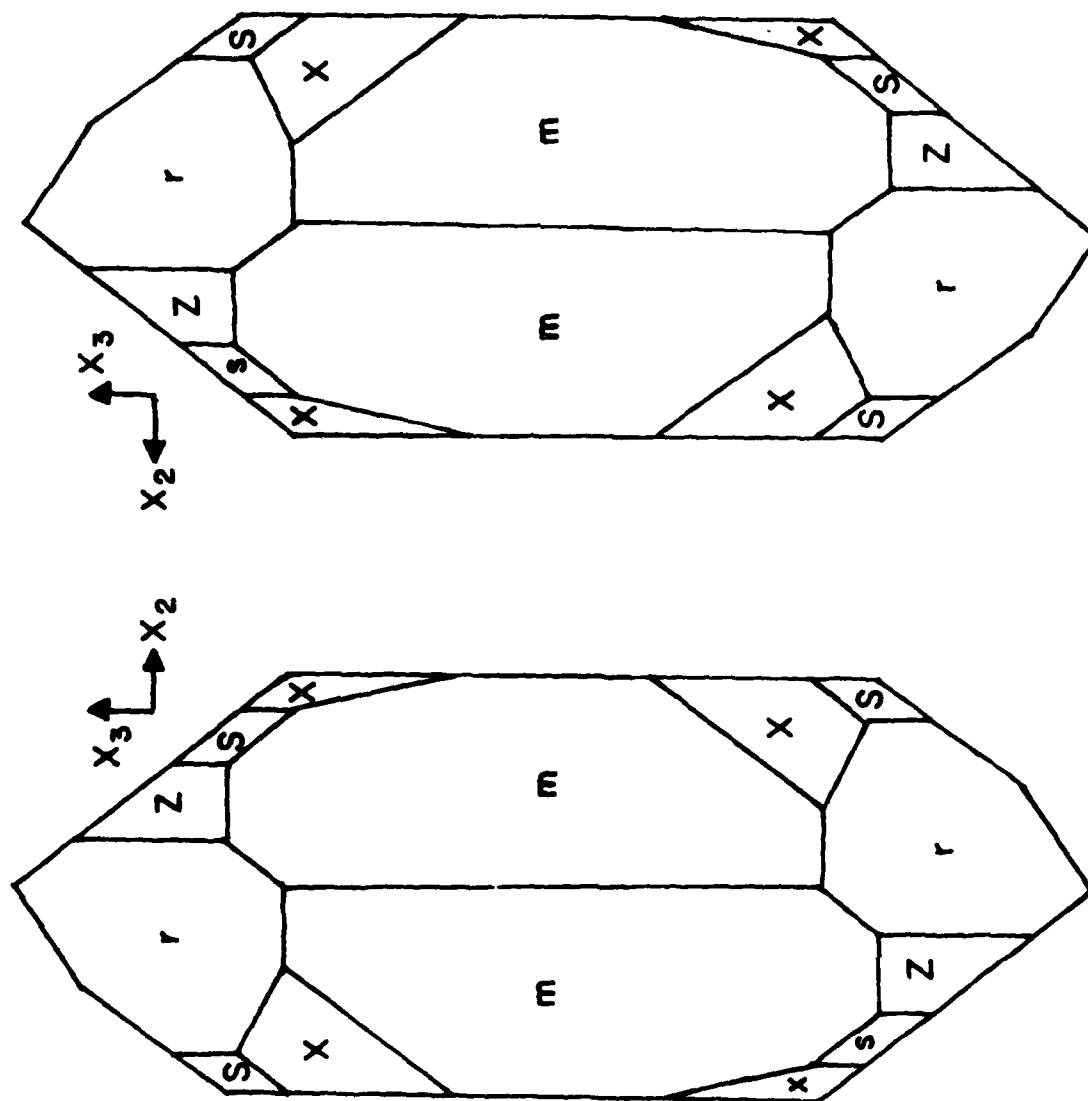


Figure 8. Quartz pairs. Looking down  $-X_1$ .

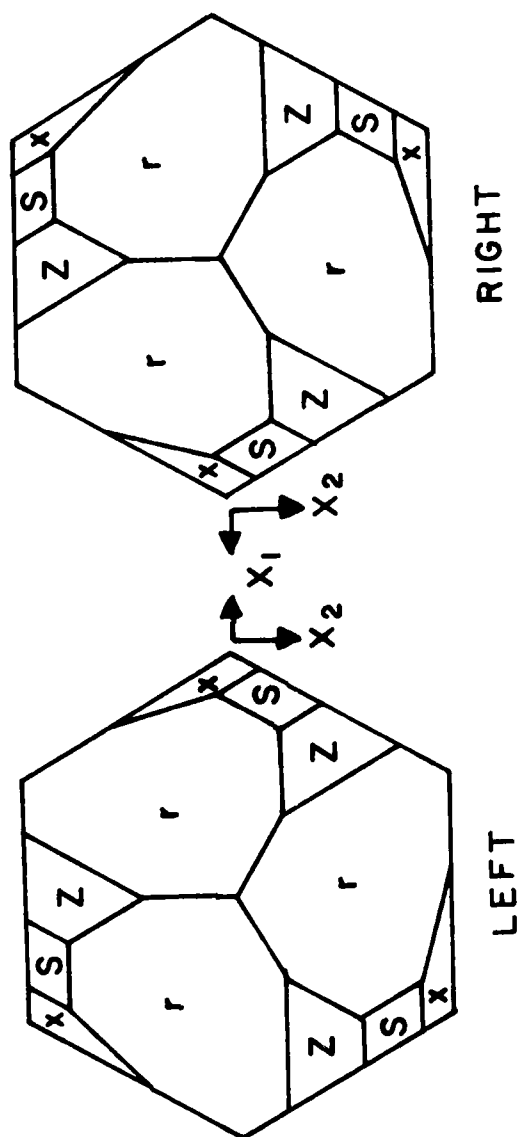


Figure 9. Quartz pairs. Looking down  $+X_3$ .

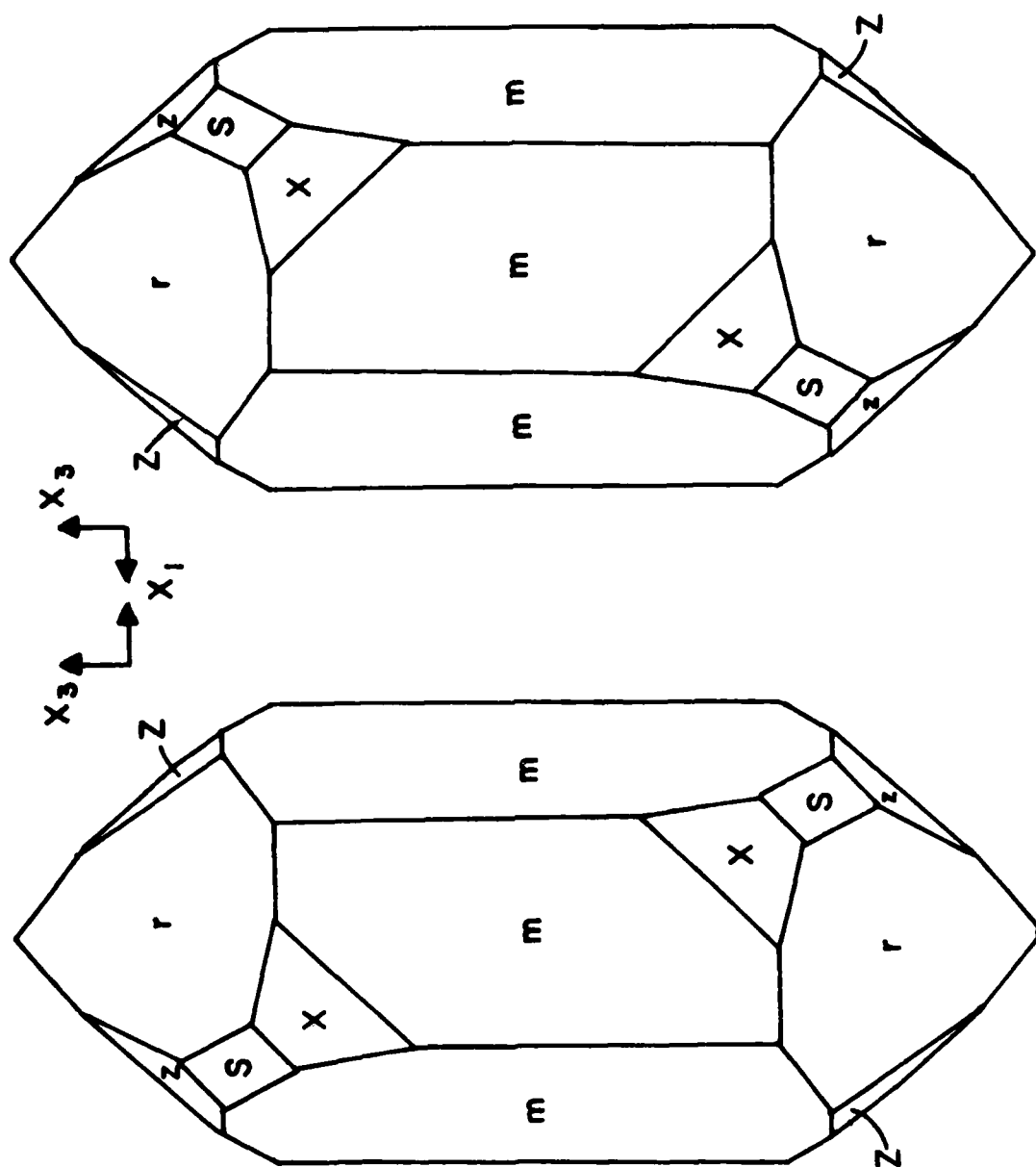


Figure 10. Quartz pairs, Looking down  $+X_2$ .

# ELECTRICAL AND OPTICAL TWINNING

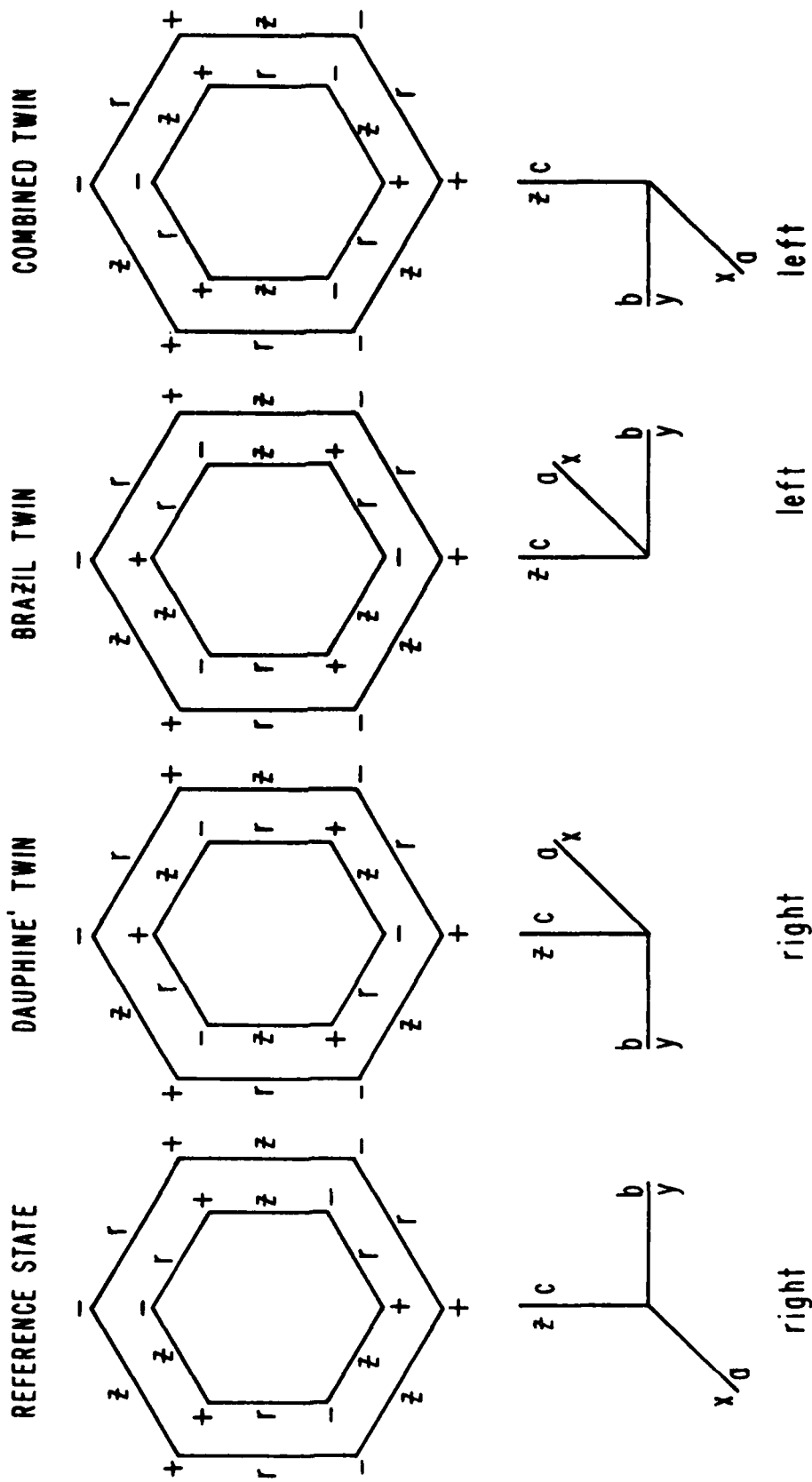


Figure 11. Electrical and optical twinning.

Figure 12 shows three examples of cultured quartz bars, with their associated seeds. The "minor rhomb plate" is grown to facilitate cutting AT cuts, since this cut is nearly parallel to the minor rhombohedron of the crystal, i.e., to the faces marked "z" in Figures 6 to 10. The Y-bar is grown from a seed with length along the Y axis; this axis is the direction of slowest growth. The z-bar grows from a basal plane seed. Photographs of left-handed and right-handed Y-bars are shown in Figures 13 to 20. Odd-numbered figures are left-quartz; even are right-quartz. These are shown as paired enantiomorphs in Figures 21 to 24. The left-hand sample is at the top in each figure. Right- and left-handed cultured quartz bars ("Y-bars") are shown as line drawings in Figures 25 and 26, respectively;<sup>77</sup> also indicated are the natural "r", "m", and "z" faces, and the orientation of the AT cut.

If a left- and a right-handed AT cut are oriented so that their axes are respectively antiparallel, and connected electrically in series or in parallel, then the combination becomes insensitive to acceleration fields of arbitrary orientation, provided that the symmetry of the mountings is maintained.<sup>53,55</sup> This is the discrete configuration, where the crystal plates are physically unjoined.

#### STACKED-CRYSTAL STRUCTURES

The stacked-crystal configuration came about originally for filters<sup>60-64</sup> when used in the multimode configuration. Layered structures utilizing a single mode have been more commonly used.<sup>78-92</sup> Here we discuss the stacking of two enantiomorphous pairs with respective axes antiparallel, and operated as a single resonator of composite form. Both crystals are of identical design; that is, they have identical individual frequencies, electrode patterns, and so forth. Figure 27 gives the four possible two-crystal structures. The two on the left in the figure are connected electrically in series; the two on the right are in parallel electrically. The upper two are arranged so that the electric fields in the two crystal plates are antiparallel; the bottom two structures have electric fields that are parallel in the two crystals. For the upper structures, the odd harmonics (of the composite taken as a whole) are driven, while the even harmonics are driven in the two lower structures. In the upper left and lower right configurations, an insulating film or layer between the crystals is necessary for operation, and large values of capacitance would be associated therewith, to the detriment of the composite's performance. This leaves the two configurations of Figure 28 as the simplest and most practical stacked crystal resonators for acceleration immunity. The structure on the left of the figure consists of two crystal plates connected electrically in parallel, using a common central electrode. It operates at odd harmonics of the fundamental frequency of the composite, i.e., at one half, three halves, etc., of the frequency of each crystal plate operated separately.

The structure on the right side of Figure 28 is the series version of the stack, and operates at even harmonics. A central electrode is not even necessary in this configuration. Provided the plates to be joined have flat mating surfaces and are sufficiently clean of contaminants, they will adhere due to van der Waals forces. An apparatus that can be used for this purpose is nearing completion.<sup>93</sup>

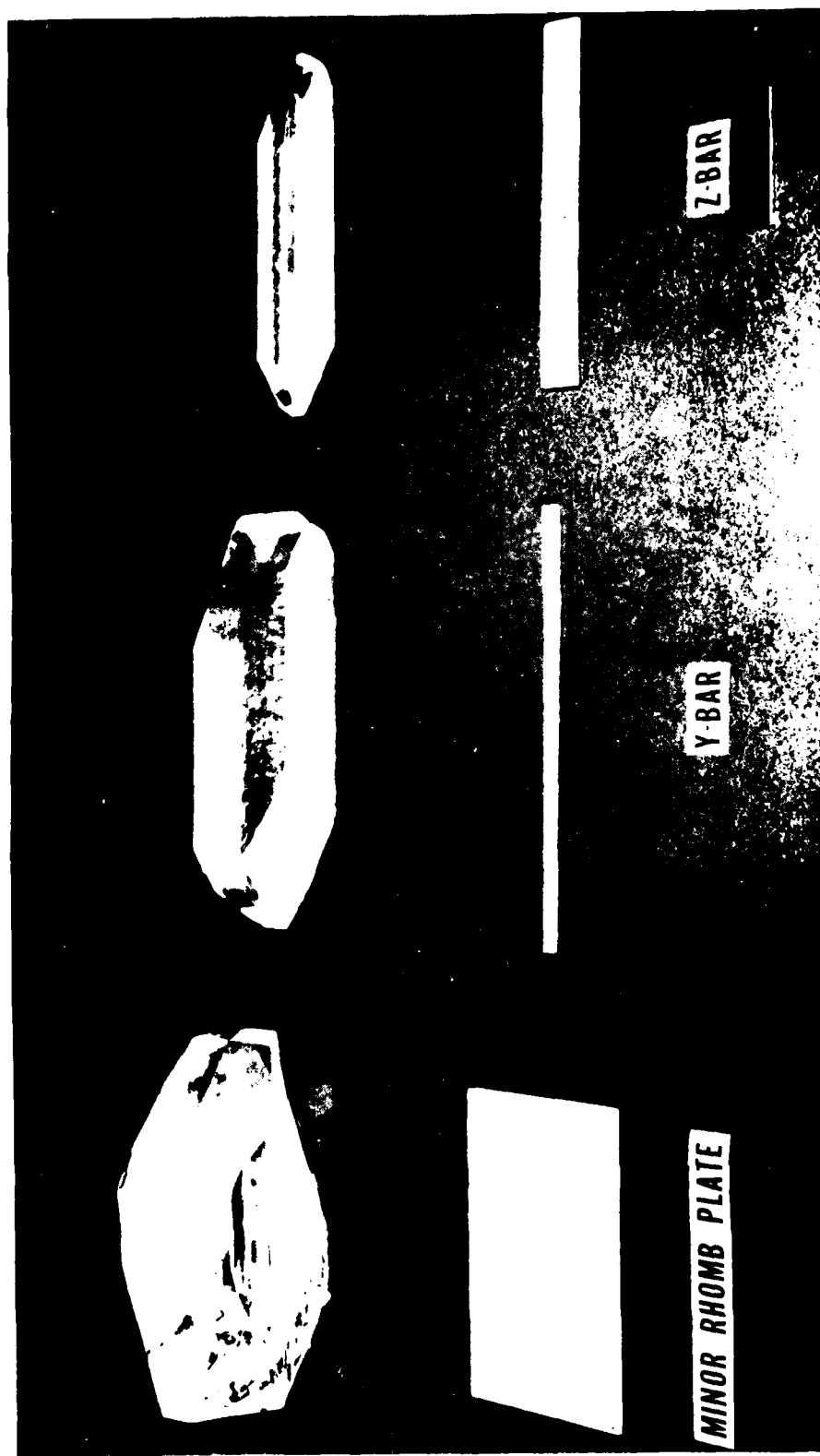


Figure 12. Cultured quartz bars.

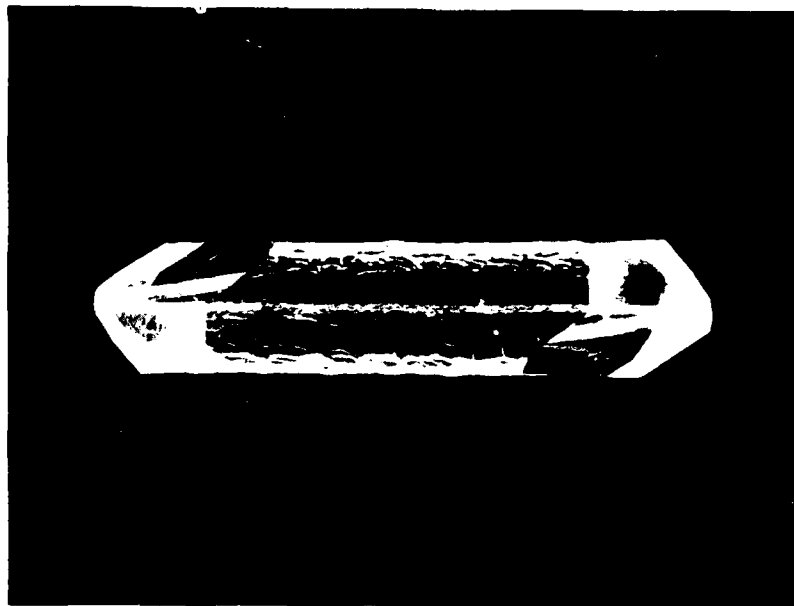


Figure 13. Left-handed quartz Y-bar. Twin of Figure 14.

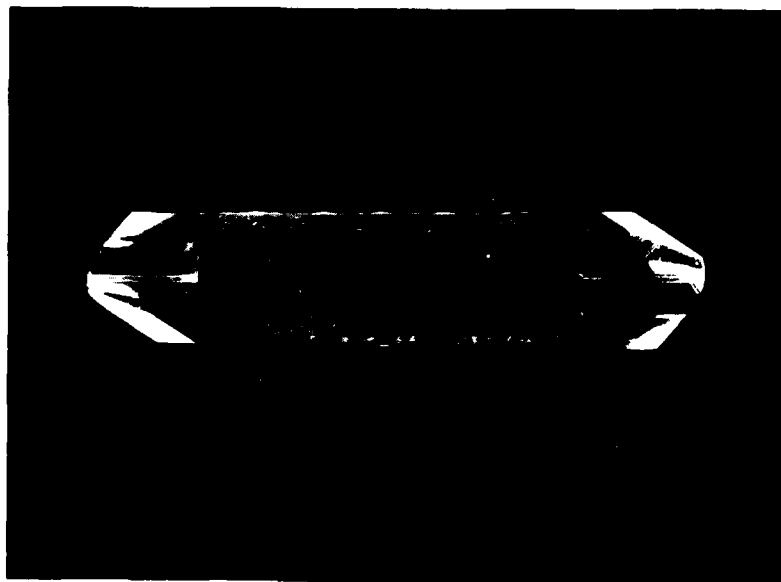


Figure 14. Right-handed quartz Y-bar. Twin of Figure 13.

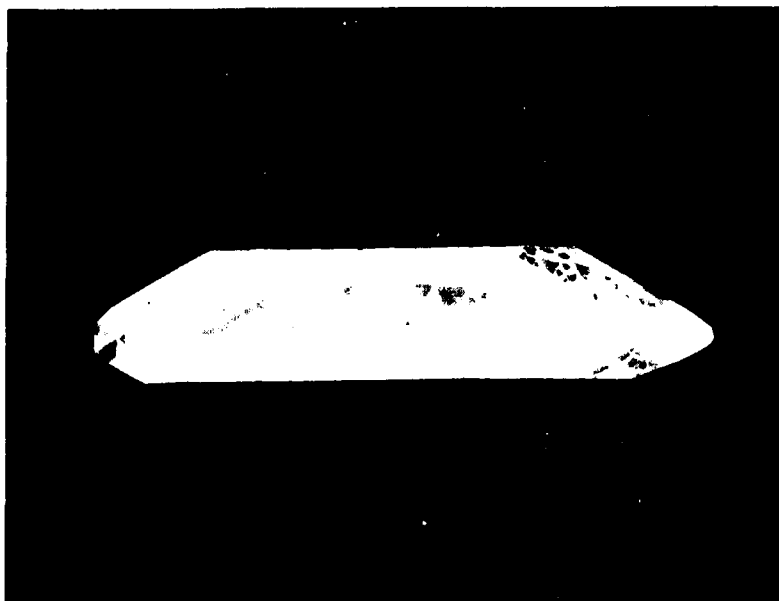


Figure 15. Left-handed quartz Y-bar. Twin of Figure 16.



Figure 16. Right-handed quartz Y-bar. Twin of Figure 15.

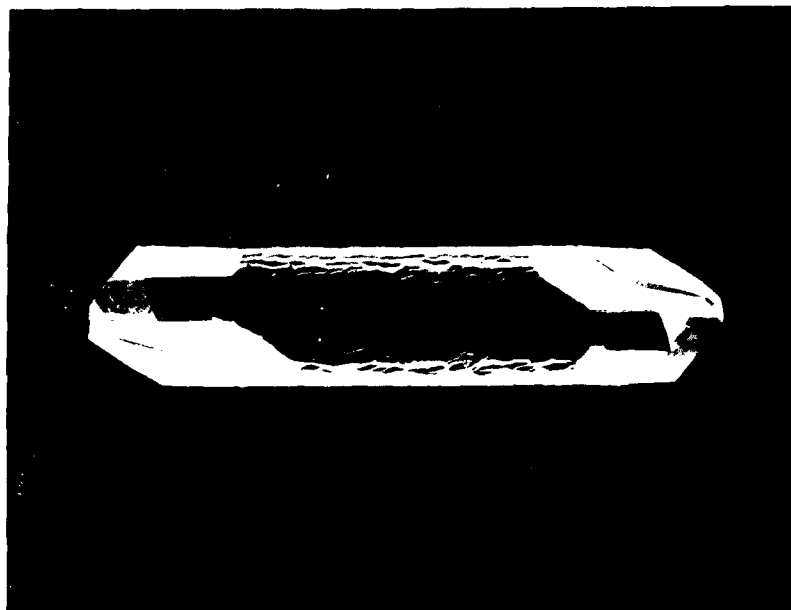


Figure 17. Left-handed quartz Y-bar. Twin of Figure 18.

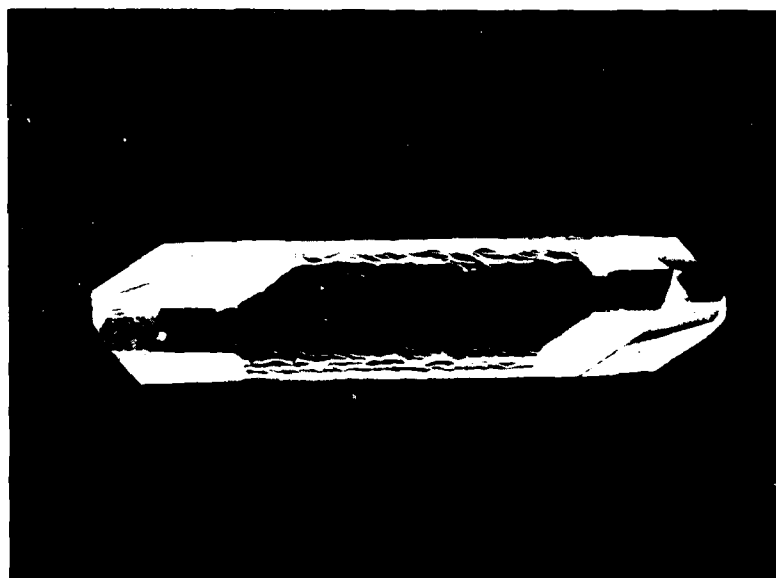


Figure 18. Right-handed quartz Y-bar. Twin of Figure 17.

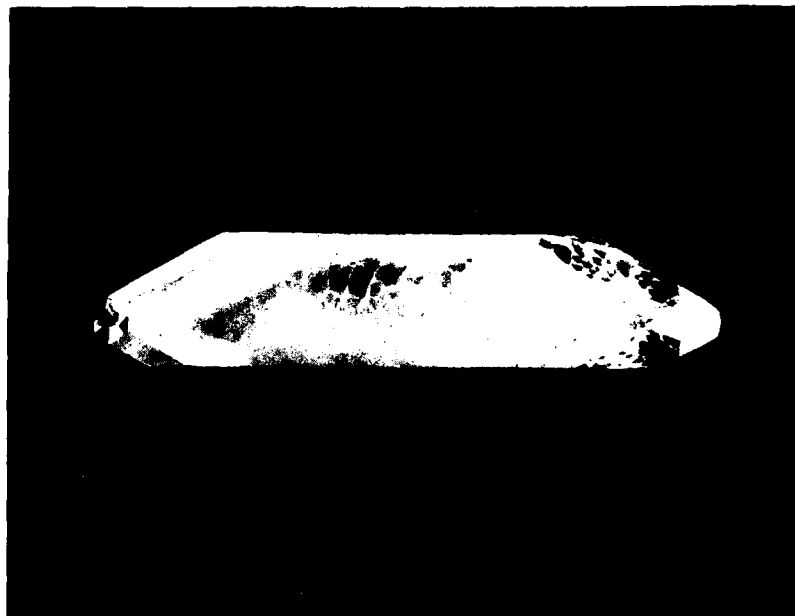


Figure 19. Left-handed quartz Y-bar. Twin of Figure 20.

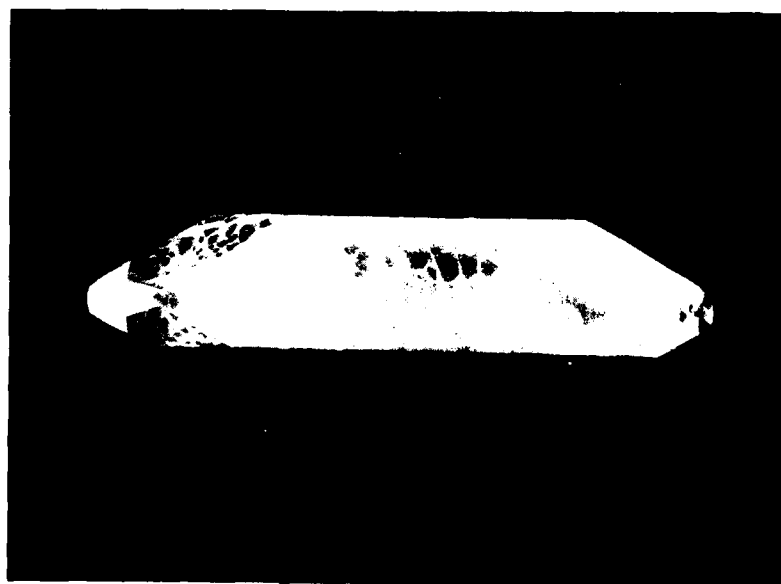


Figure 20. Right-handed quartz Y-bar. Twin of Figure 19.

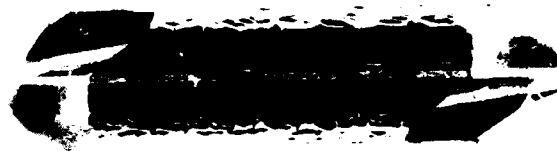
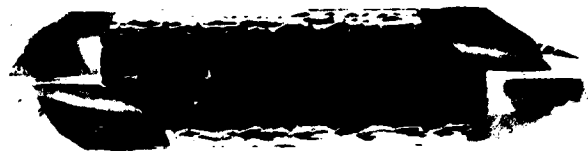


Figure 21. Twin pairs of Figure 13 (top) and Figure 14.

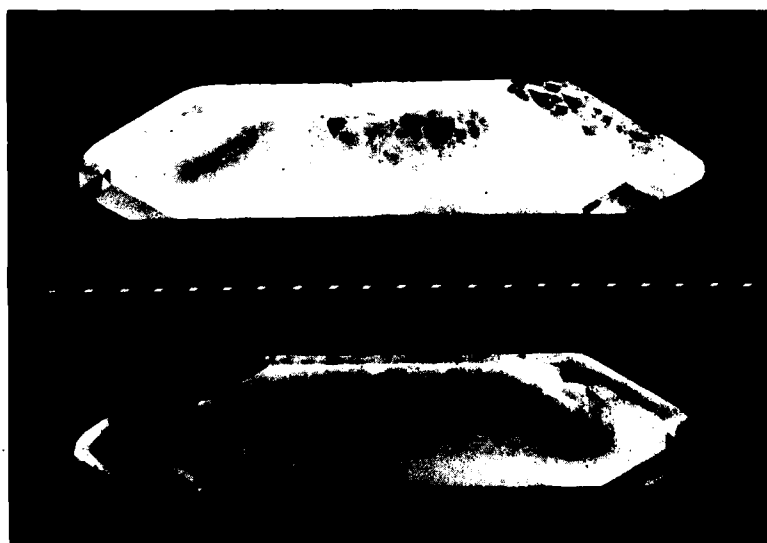


Figure 22. Twin pairs of Figure 15 (top) and Figure 16.

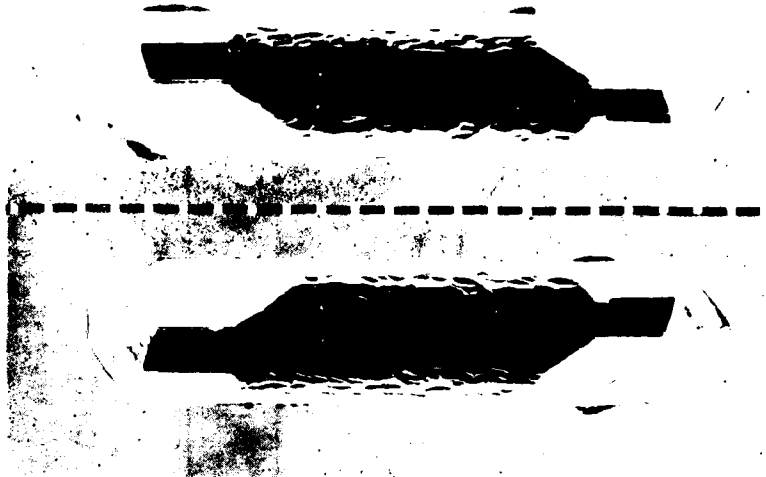


Figure 23. Twin pairs of Figure 17 (top) and Figure 18.

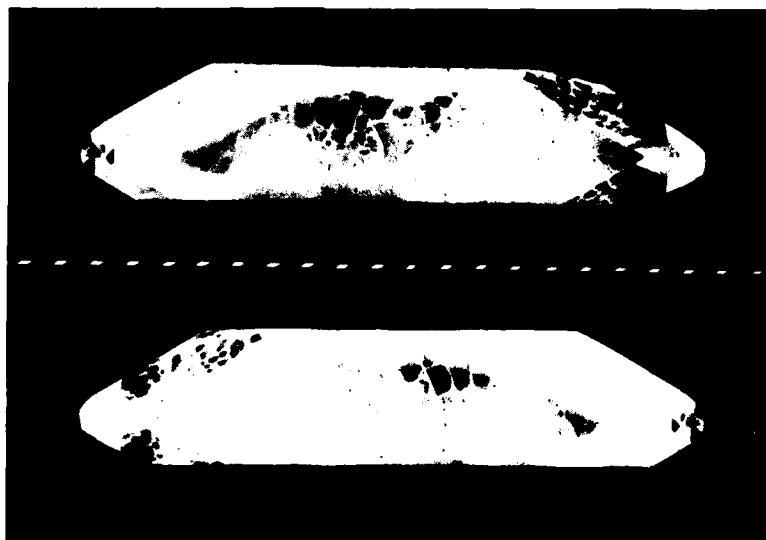


Figure 24. Twin pairs of Figure 19 (top) and Figure 20.

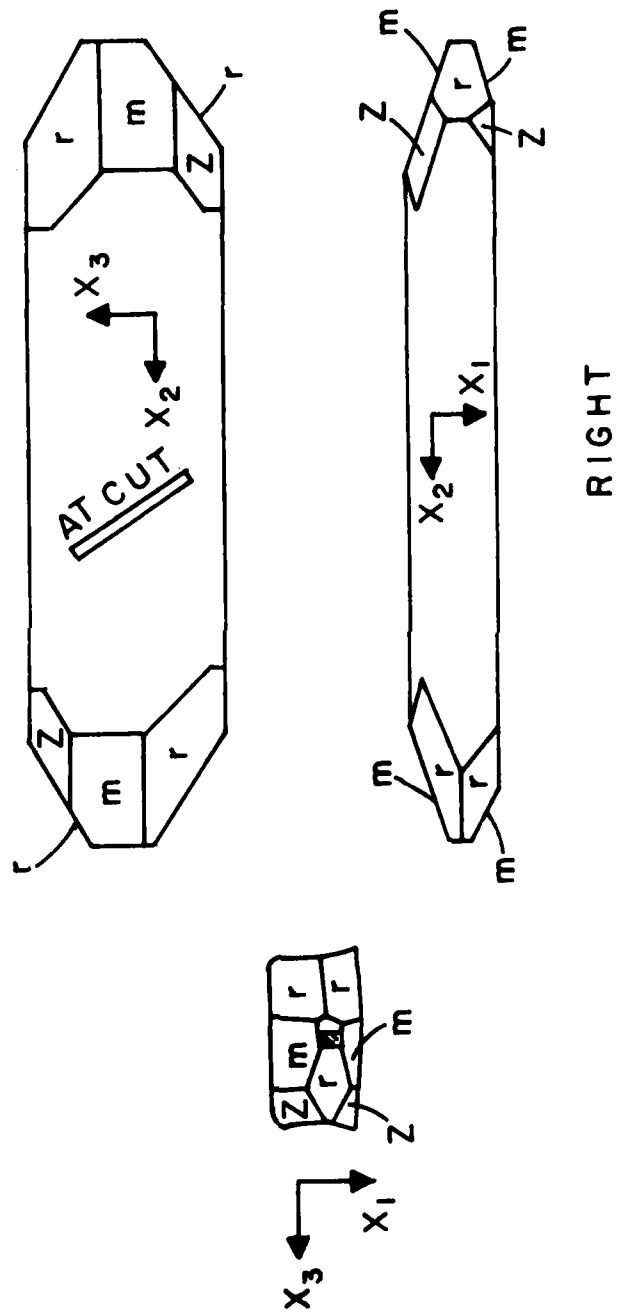


Figure 25. Cultured quartz bar, right-handed.

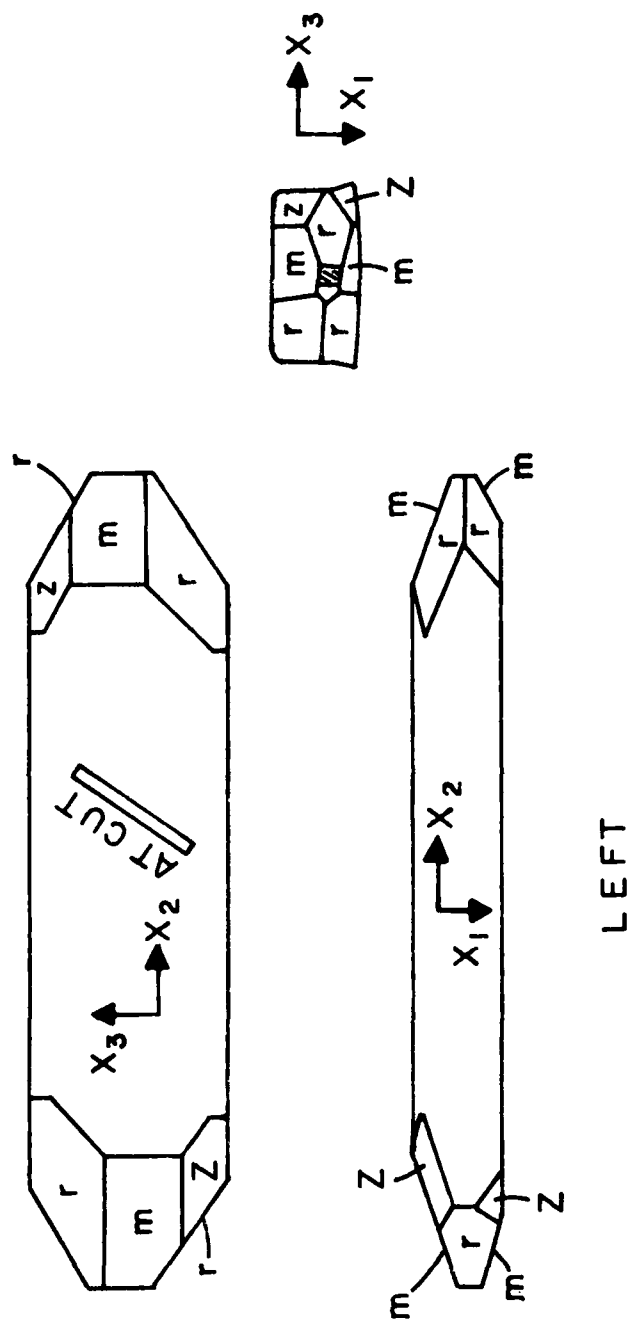


Figure 26. Cultured quartz bar, left-handed.

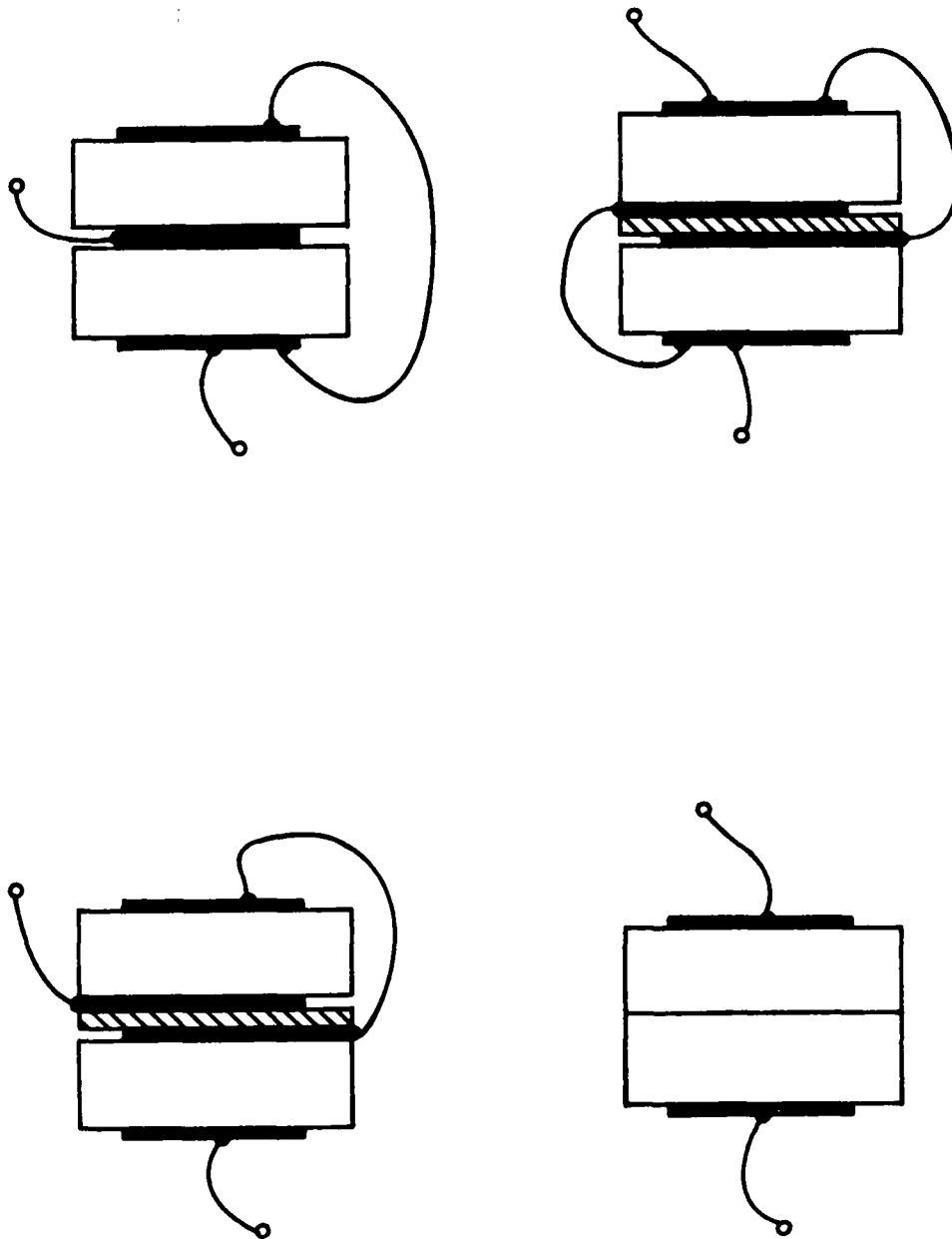


Figure 27. Stacked-crystal vibrator configurations.

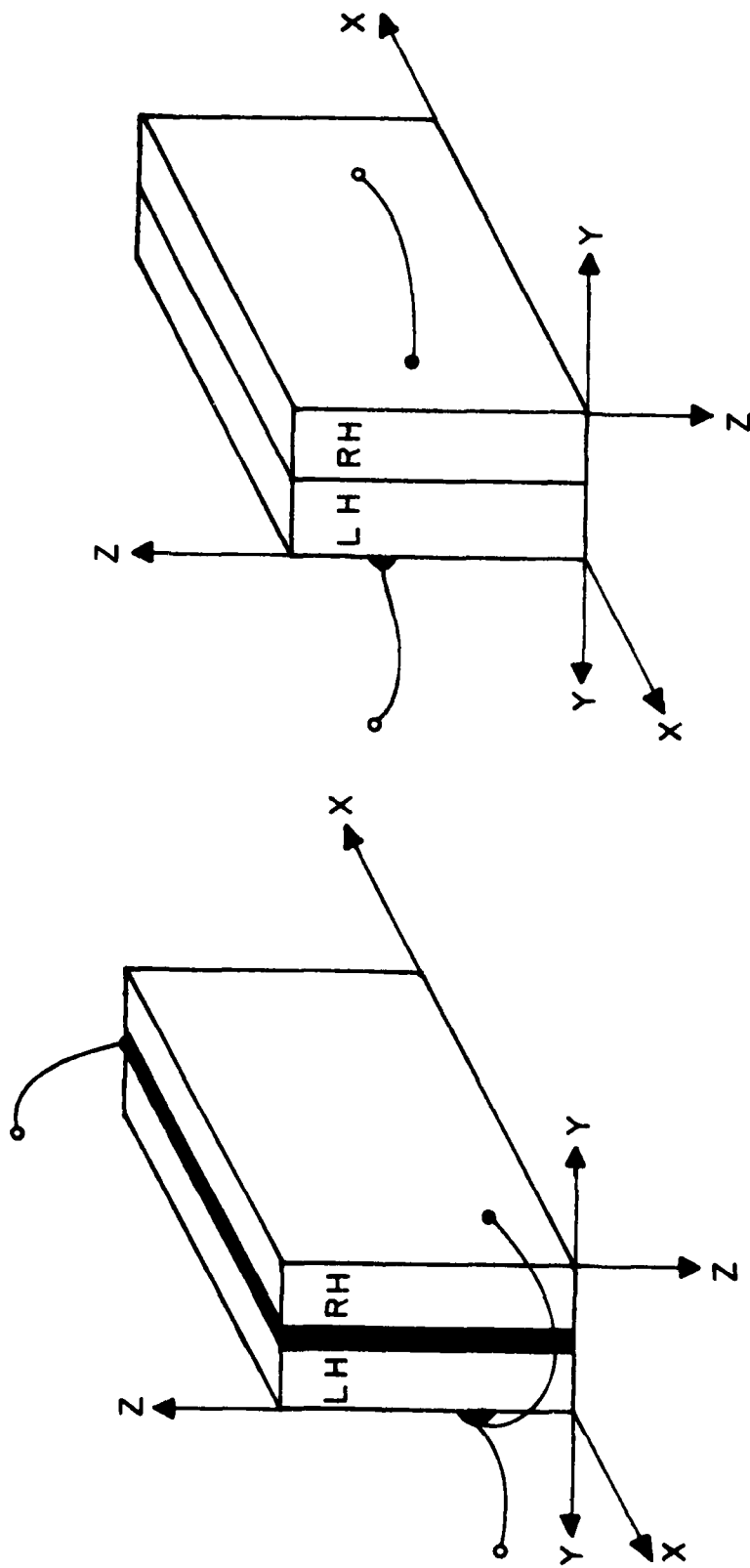


Figure 28. Simplest stacked-crystal vibrators.

Implicit in the discussion above have been assumptions that the stacked crystal composite vibrator consists of two crystal twins that each operate in a single mode, and that, when the two vibrators are joined, the composite continues to operate in this manner. For the singly rotated cuts ( $YX_2$ ) of quartz, including the AT and BT cuts, it is easy to see that this will be the case, since each vibrator is driven in a pure shear mode by a thickness-directed electric field. This mode has particle motion strictly in the plane of the plate, so that when the two plates are joined, the composite will also have motions in the plane of the plate; the phase of the motions in the two component plates will depend on how the electrodes are connected, and hence, on whether the electric fields in the two plates are parallel or antiparallel. The phase will dictate whether even or odd harmonics of the composite are driven.

The most important recent development in the area of high precision frequency control has been the introduction of doubly rotated cuts of quartz, (in particular the SC cut), having compensation of certain nonlinear elastic effects that otherwise cause very undesirable stress-frequency<sup>94,95</sup> and thermal transient/thermal gradient-frequency effects.<sup>96-101</sup> The definition of singly and doubly rotated cuts is shown in Figure 29, along with the loci of zero temperature coefficient cuts for quartz, for the faster shear mode ("b-mode"), shown dashed, and the slower shear mode ("c-mode"), shown as solid lines. It is an experimentally observed fact that SC cuts are also considerably less sensitive to the effects of acceleration (attitude, shock and vibration) than AT cuts; the improvement may be as much as a factor of ten. For doubly rotated crystal cuts the three piezoelectrically driven modes all have particle motion that is neither parallel to, nor perpendicular to, the plate normal. It is not clear, therefore, that such plates can be used in the stacked configuration for acceleration compensation in the manner described above. This will now be demonstrated.

The angles specifying the particle displacement are shown in Figures 30, 31, and 32 for the "a", "b", and "c" modes, respectively, along the upper locus seen in Figure 29; the angles are defined in Reference 54.

#### DOUBLY ROTATED ENANTIOMORPHS

Both singly and doubly rotated enantiomorphs are shown in Figure 33. It is seen that the mirror-image property holds for any orientation. Assume that a doubly rotated cut, e.g., the SC cut, has been fashioned in both right- and left-handed forms; also assume that the corresponding plate axes have been simply labeled X, Y and Z (instead of double-prime axes). Now suppose that a portion of each plate is considered to have dimensions such that the eigenvector corresponding to the mode in question points in the direction from an origin "O" along a major diagonal of the rectangular prism as seen in Figure 34. On the left is the left-handed plate (or portion thereof), with particle motion along "OA"; the motion thus has components both along and perpendicular to the major plate surfaces. The mirror image right-handed plate seen in the center of Figure 34 has particle motion along "OB", because "OB" is the mirror image of "OA". In order to orient the right-handed plate so that its axes are antiparallel to those of the left-handed plate, and thereby achieve the configuration for acceleration compensation, it is only necessary to rotate the center drawing in Figure 34 about the Y axis until the rightmost drawing is reached. Then the line "OB", seen in the right portion of the figure is exactly in line with "OA" seen in

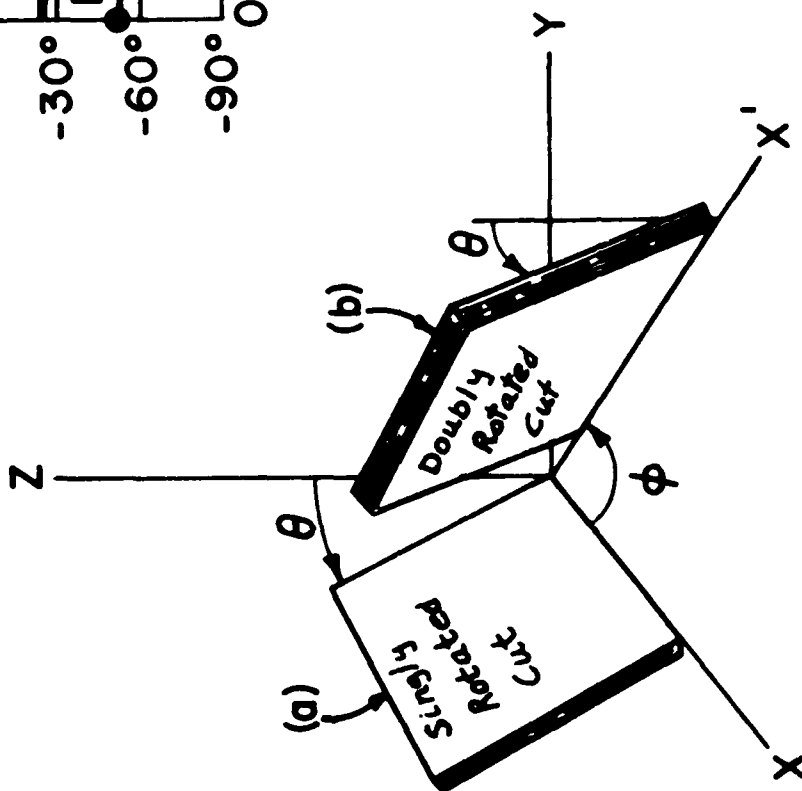
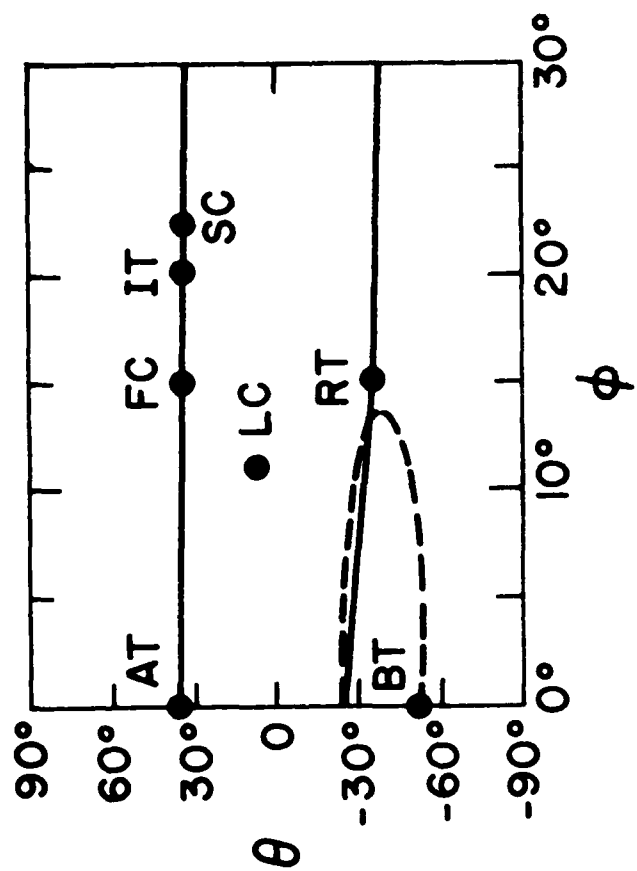


Figure 29. Doubly rotated quartz cuts.

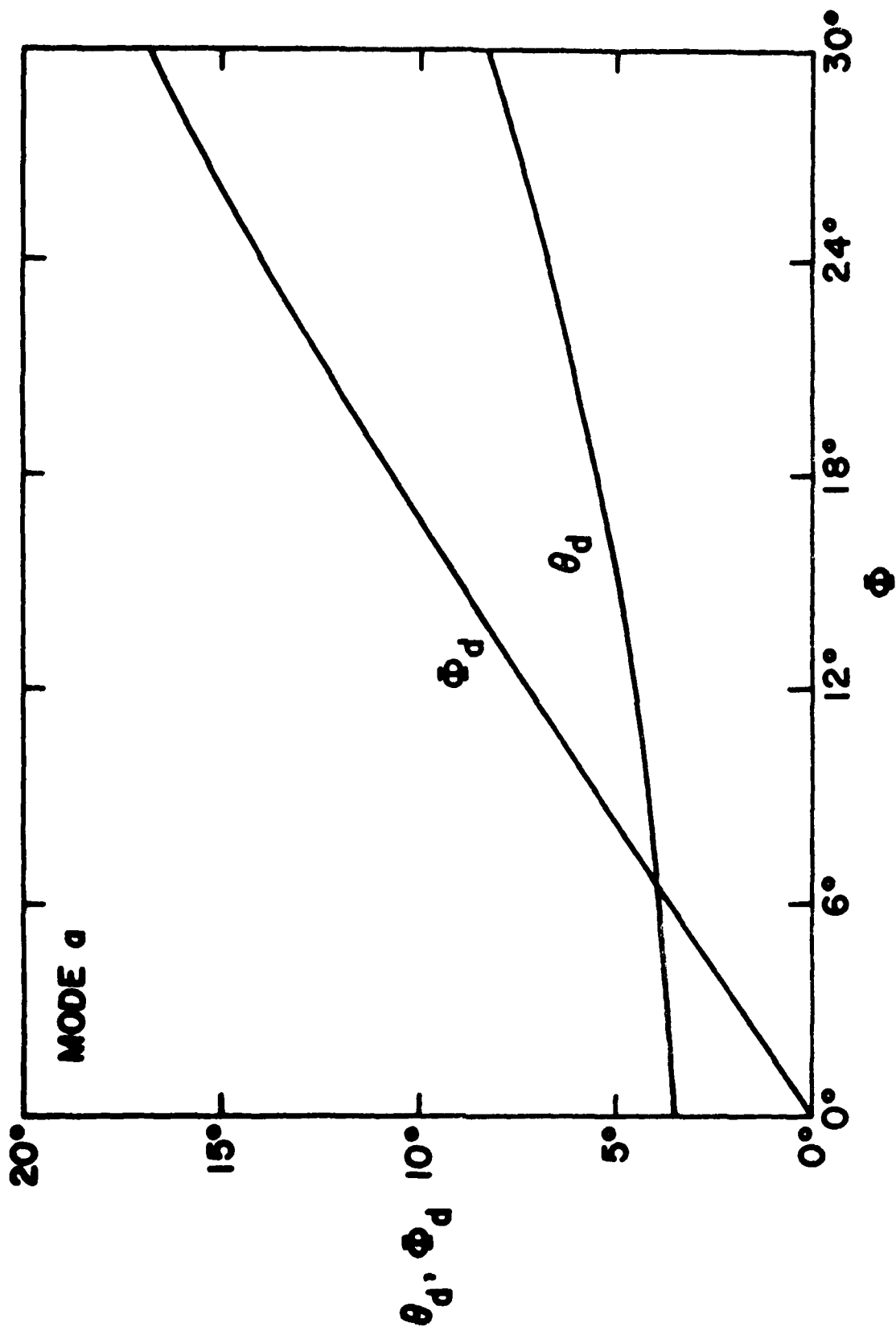


Figure 30. Particle displacement angles. Mode a.

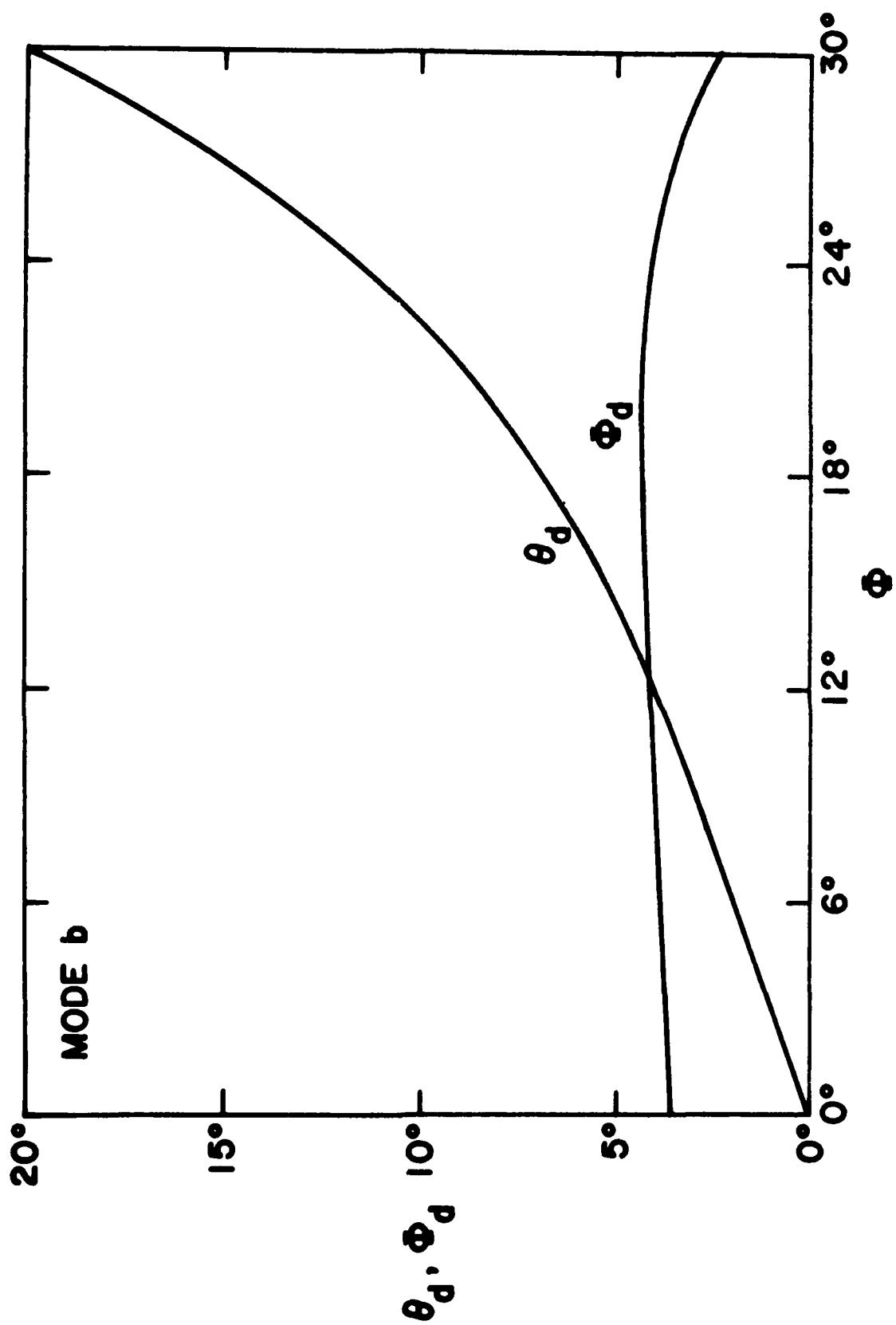


Figure 31. Particle displacement angles. Mode b.

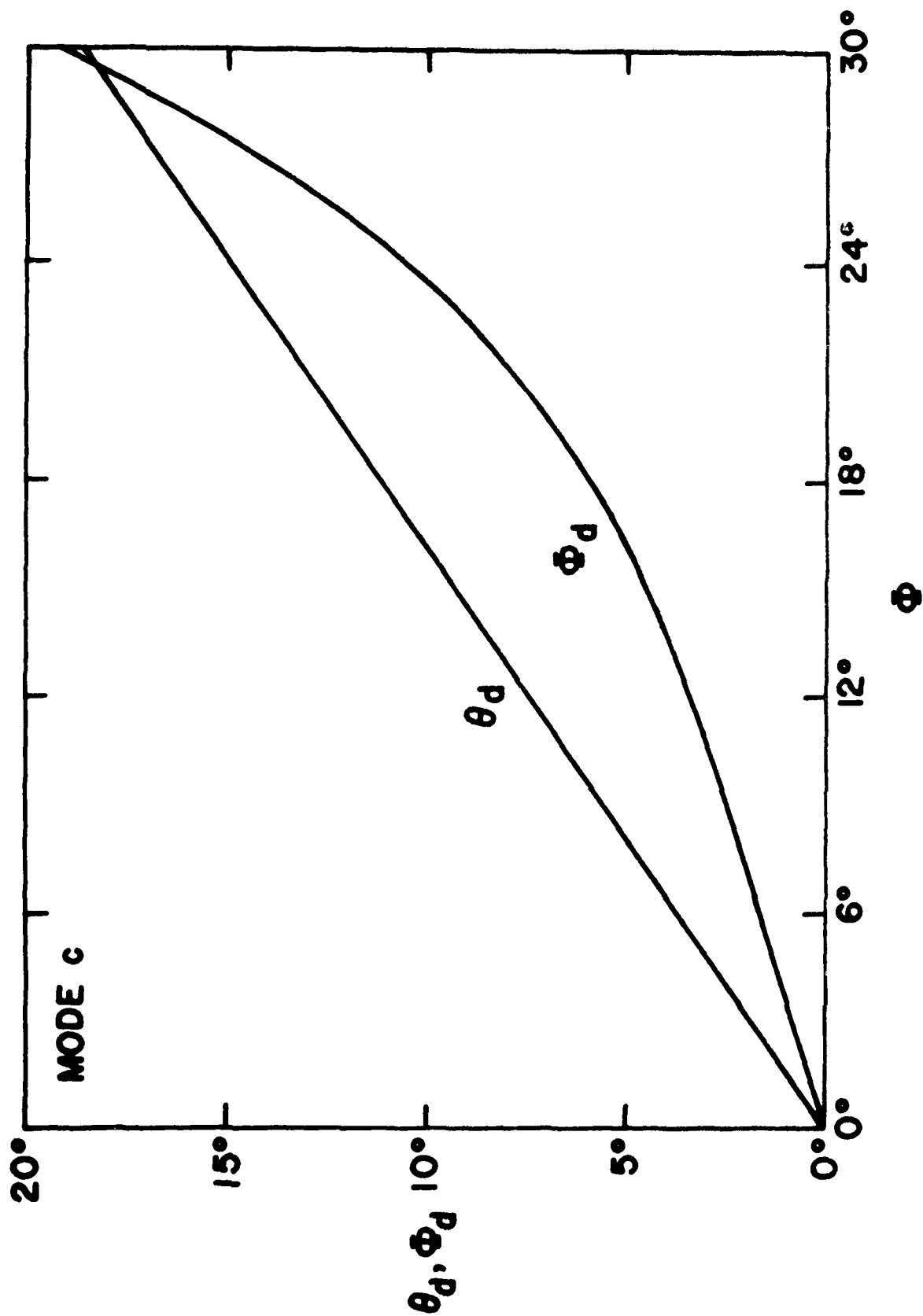


Figure 32. Particle displacement angles. Mode c.

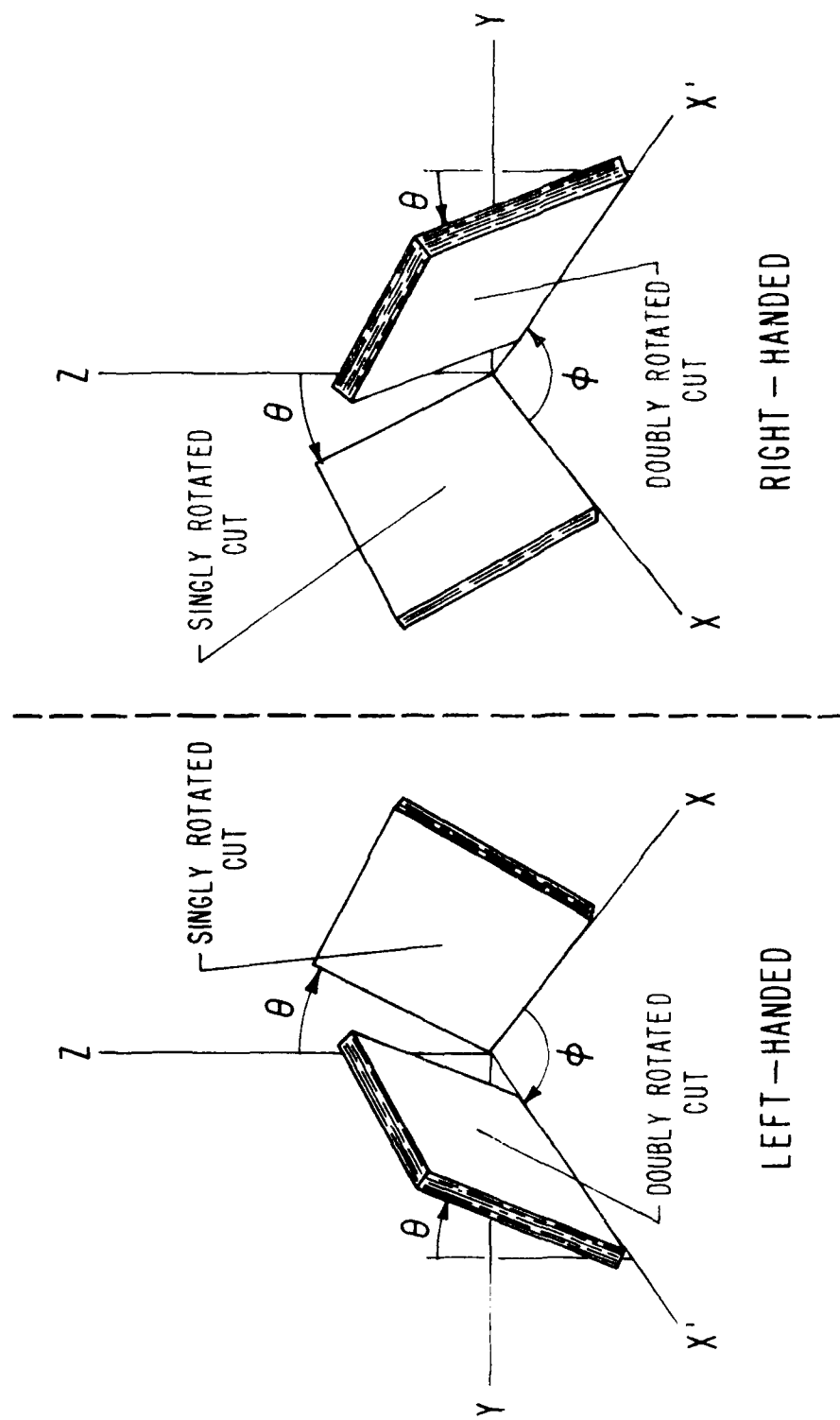


Figure 33. Singly and doubly rotated enantiomorphs.

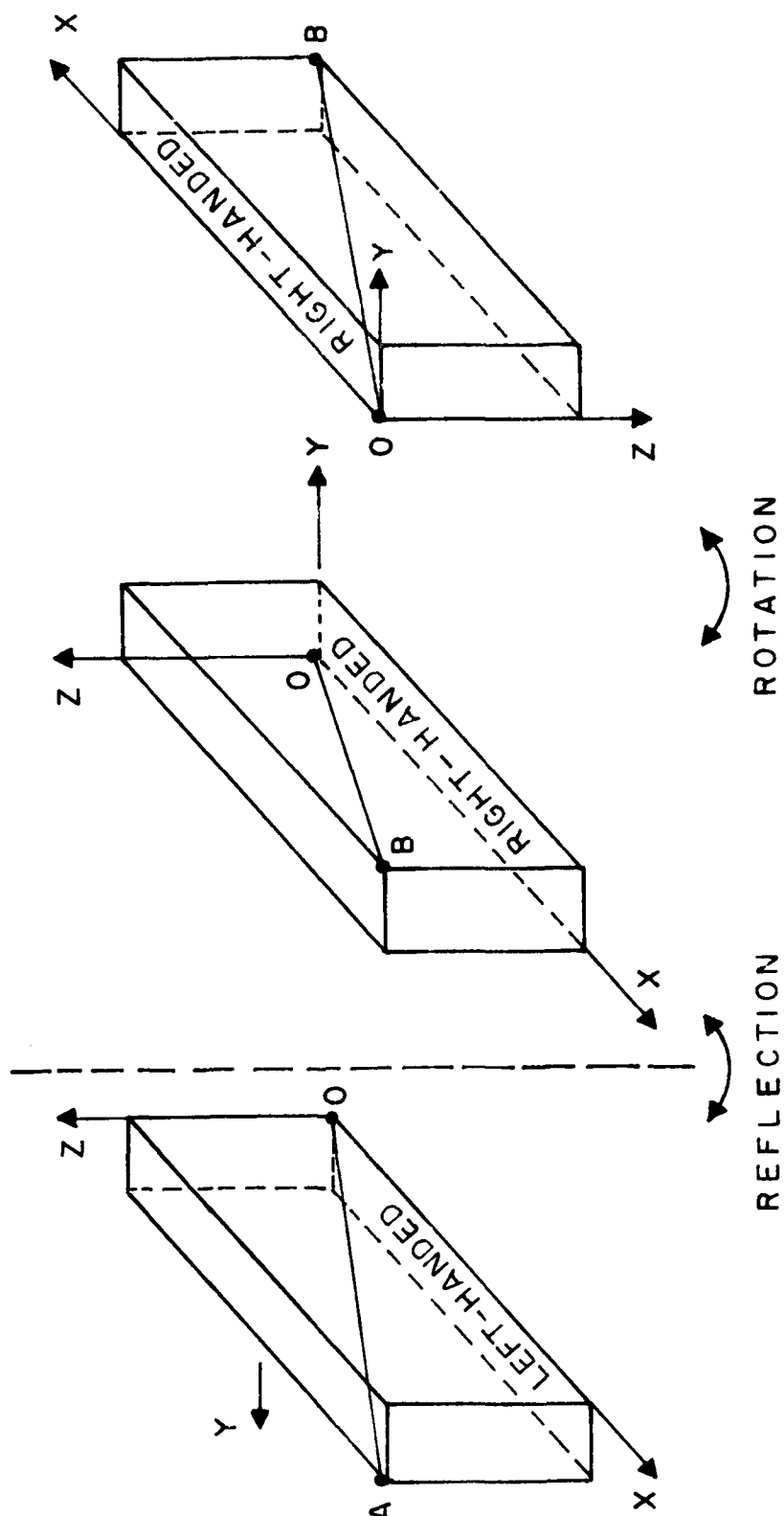


Figure 34. Parallel displacements in enantiomorphs.

the left portion of the figure. The stacking thus can take place without any difficulty; the argument holds for all three plate thickness modes, with the conclusion that doubly rotated plates may be stacked as readily as singly rotated plates, and no problem of introducing additional mode coupling will arise, provided the corresponding axes are either all parallel (two plates of the same handedness) or all antiparallel (two plates of opposite handedness).

Realization of acceleration compensation in the manner set forth in this report requires the availability of quartz bars of both handednesses. Almost all of the cultured quartz Y-bars produced today are right-handed, although left-handed bars can be obtained on special order. For the purpose of making doubly rotated SC cuts in the same manner as AT cuts, it is possible to grow rotated Y-bars ("SC-cut bars") by using a seed with length in the  $X_2'$  direction, rotated by  $\phi \approx 22^\circ$  about the  $X_3$  axis.<sup>102,103</sup> Photographs of left-handed and right-handed SC-cut bars are shown in Figures 35 to 42. Odd-numbered figures are left-quartz; even are right-quartz. These are shown as paired enantiomorphs in Figures 43 to 46. The left-hand sample is at the top in each figure. Line drawings are shown in Figures 47 to 54 corresponding to the photographs of Figures 35 to 42, respectively. Views looking down the  $+Y_2$  and  $-Y_2$  axes for both left- and right-quartz are shown in Figure 55.

Cultured quartz Y-bars ordinarily used for AT cuts can be used directly, in place of SC-bars, to make SC cuts.<sup>104</sup> The yield is approximately 30% higher than with the rotated SC-bar. This possibility is brought about by the three-fold symmetry existing about the Z axis in quartz. A Y-cut, for example, could be made by cutting perpendicular to the  $X_2$  axis of a Y-bar. It could also be made by cutting perpendicular to either of the two other  $X_2$  axes spaced around the  $X_3$  axis at intervals of  $120^\circ$ . In either of the latter cases the area of the slices would be larger than that in the first case. In like manner, to produce SC cuts one could either rotate first around  $X_3$  from  $X_1$  by approximately  $22^\circ$ , then make the second rotation about the new  $X_1'$  axis, or one could rotate  $120^\circ + 22^\circ$ , or  $240^\circ + 22^\circ$  for the first rotation about  $X_3$ . The second choice, namely  $\phi \approx 262^\circ$  produces a rotation that leaves the new  $X_1'$  axis only about  $8^\circ$  ( $270^\circ - 262^\circ$ ) from the original  $-X_2$  axis. One is then nearly rotating about the length of the Y-bar for the second ( $\circ$ ) rotation. (Because the  $-X_2$  axis is involved, the sense of the  $\circ$  rotation is reversed). Cutting in this fashion is thus nearly as efficient as cutting ATs; one wants, however, to have the  $X_1$  dimension as long as possible. At present, approximately 40 mm along  $X_3$  is standard, and 75 to 100 mm along  $X_1$  can be readily made.

In the foregoing we have seen that it is necessary for the corresponding axes of the quartz plates to be properly identified. In particular, it is advantageous to have a simple method of determining the positive and negative  $X_1$  axes of blanks. One practical and simple method is to use chemical etching.<sup>105,106</sup> For doubly rotated SC cuts it has been shown to be a readily applicable and practical method.<sup>106</sup>

#### RING-SUPPORTED STRUCTURES

For accelerations out of the plane of the crystal plate, desensitization of acceleration-induced frequency shifts may be partially accomplished by use of ring-supported resonators<sup>107,108</sup> as shown in Figure 56. The improvement comes about by the alteration of the boundary conditions at the plate

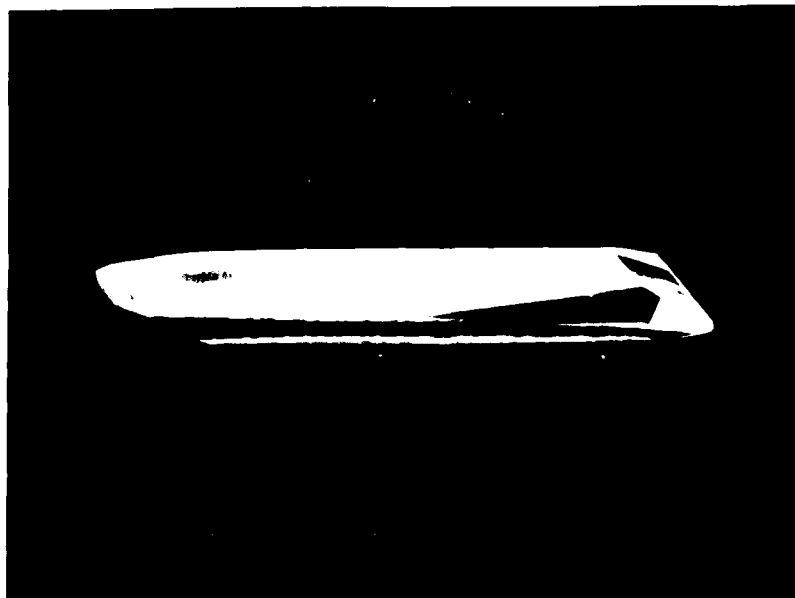


Figure 35. Left-handed quartz SC-bar. Twin of Figure 36.

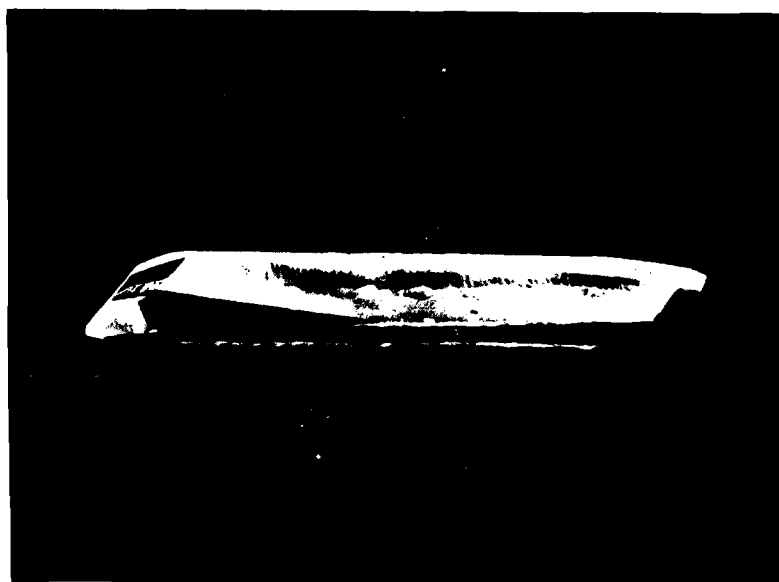


Figure 36. Right-handed quartz SC-bar. Twin of Figure 35.

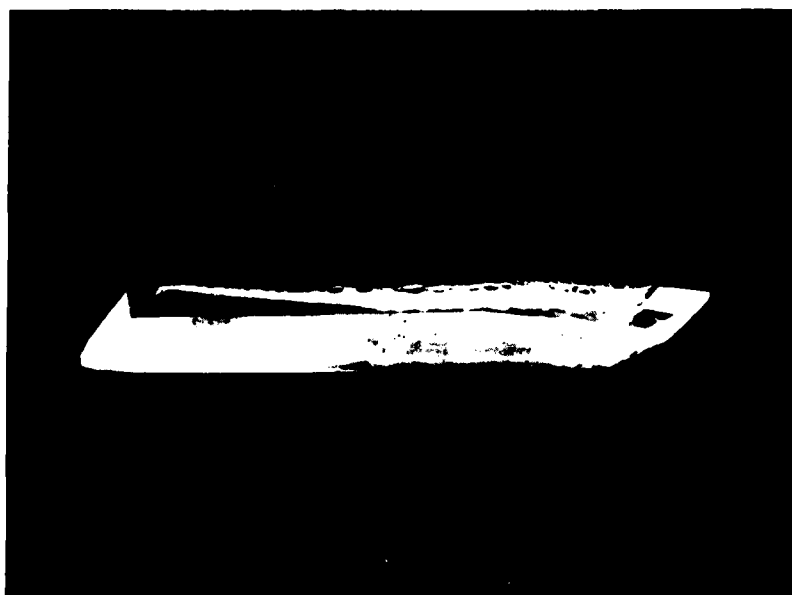


Figure 37. Left-handed quartz SC-bar. Twin of Figure 38.

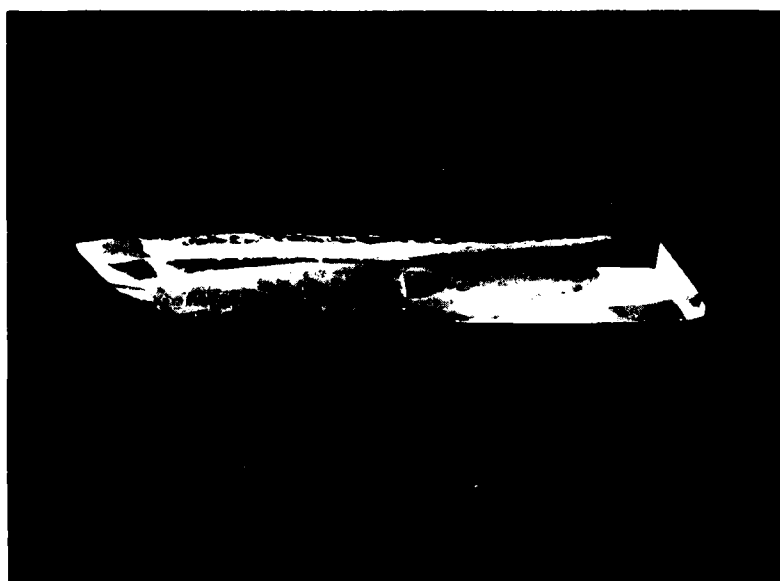


Figure 38. Right-handed quartz SC-bar. Twin of Figure 37.

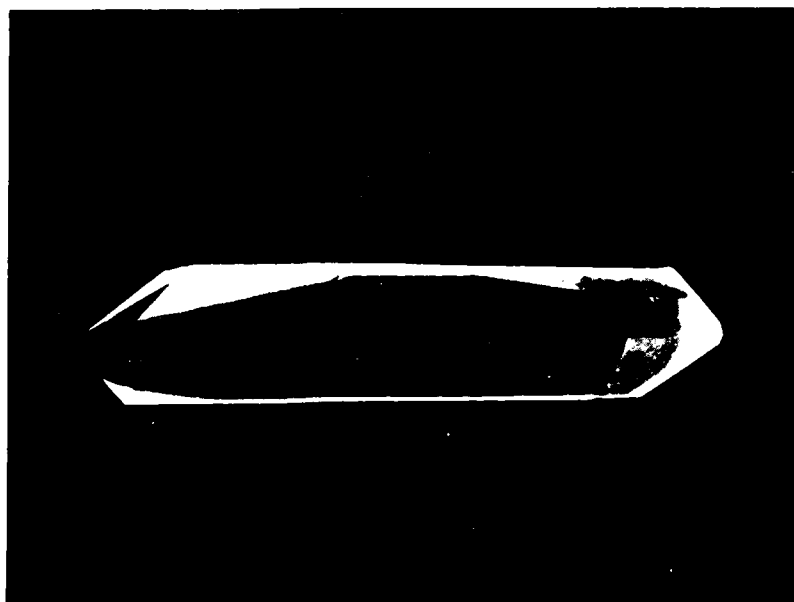


Figure 39. Left-handed quartz SC-bar. Twin of Figure 40.

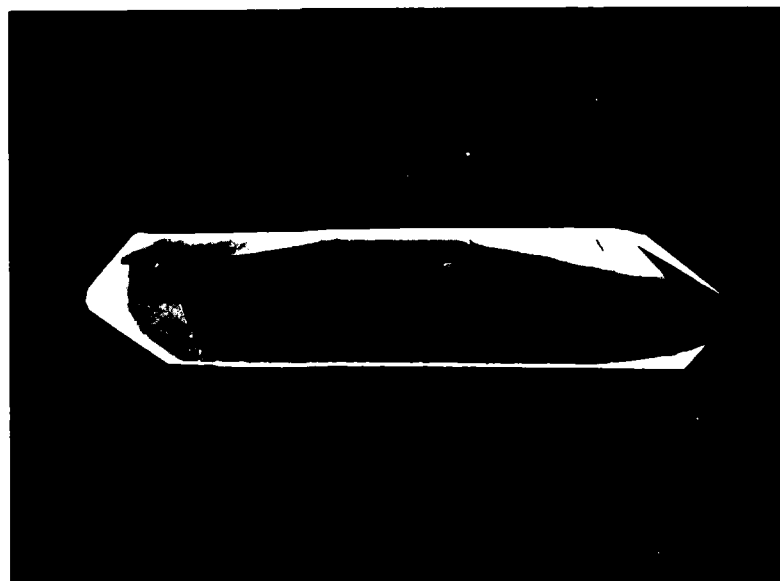


Figure 40. Right-handed quartz SC-bar. Twin of Figure 39.

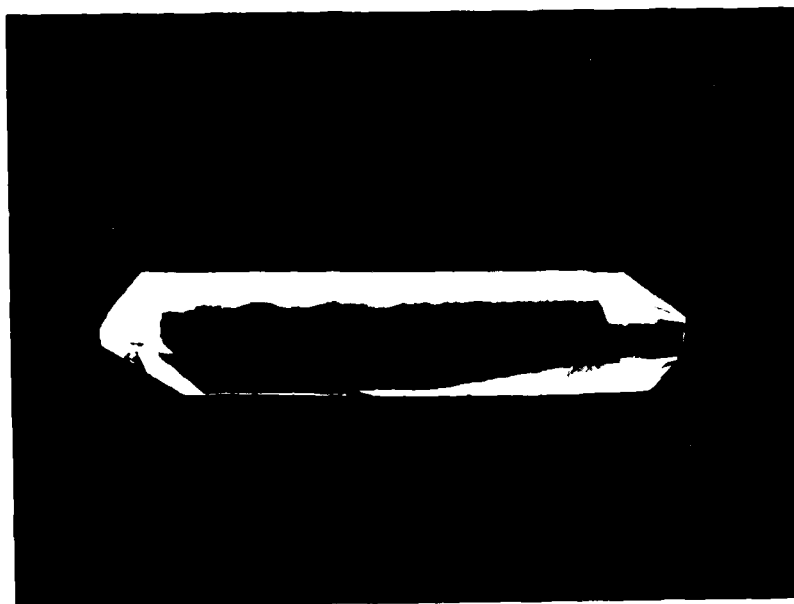


Figure 41. Left-handed quartz SC-bar. Twin of Figure 42.

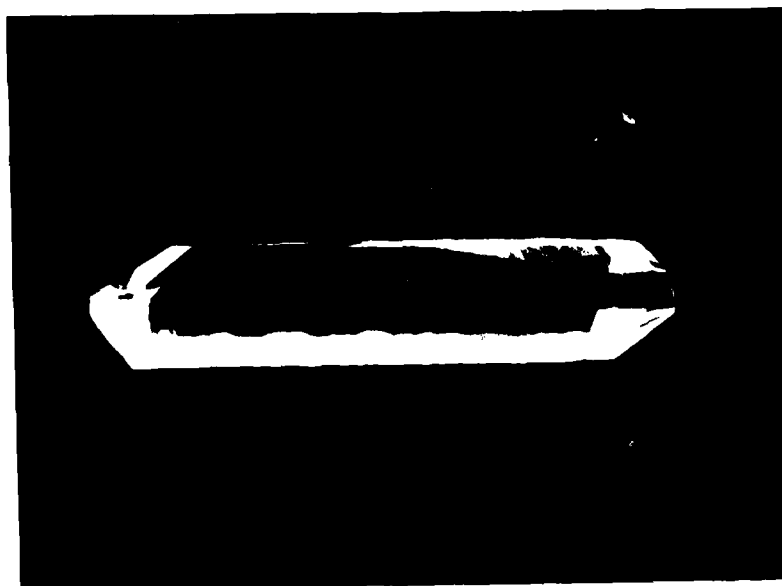


Figure 42. Right-handed quartz SC-bar. Twin of Figure 41.

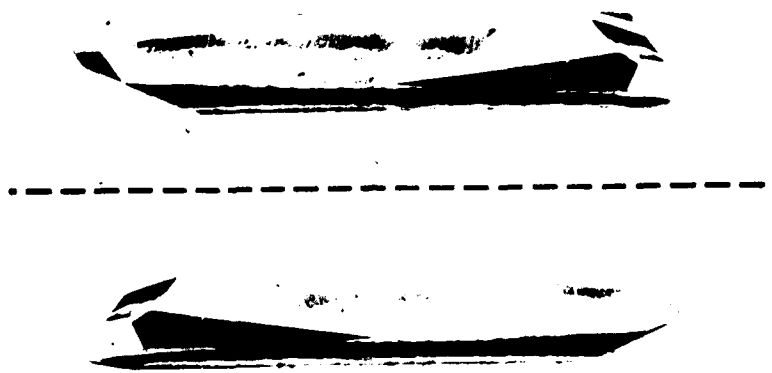


Figure 43. Twin pairs of Figure 35 (top) and Figure 36.

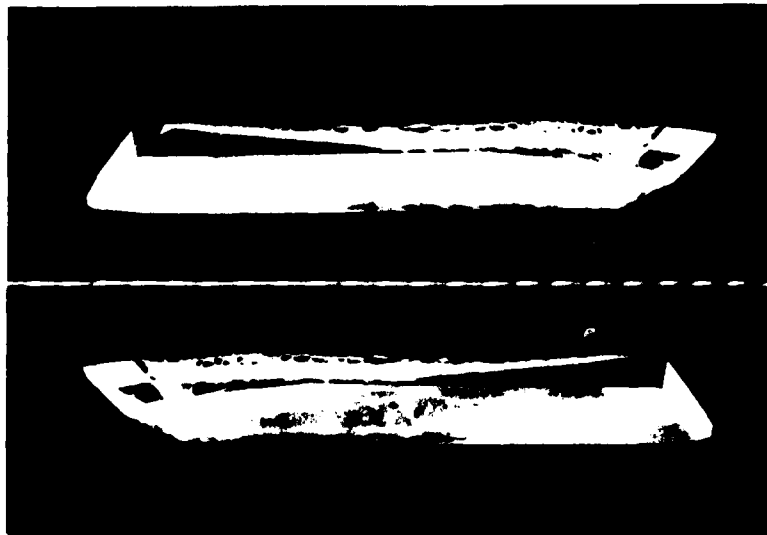


Figure 44. Twin pairs of Figure 37 (top) and Figure 38.

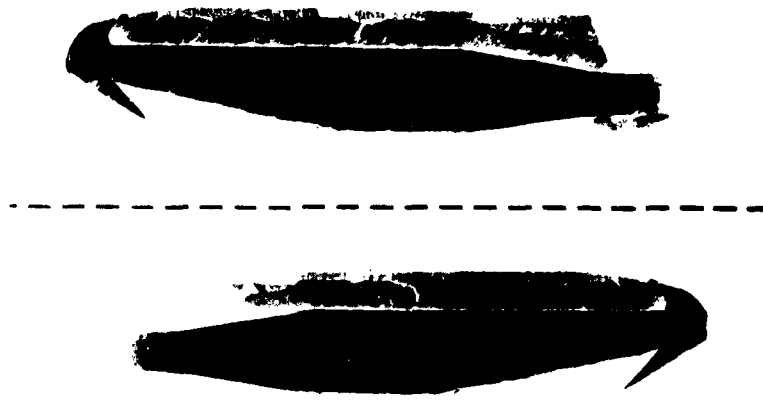


Figure 45. Twin pairs of Figure 39 (top) and Figure 40.



Figure 46. Twin pairs of Figure 41 (top) and Figure 42.

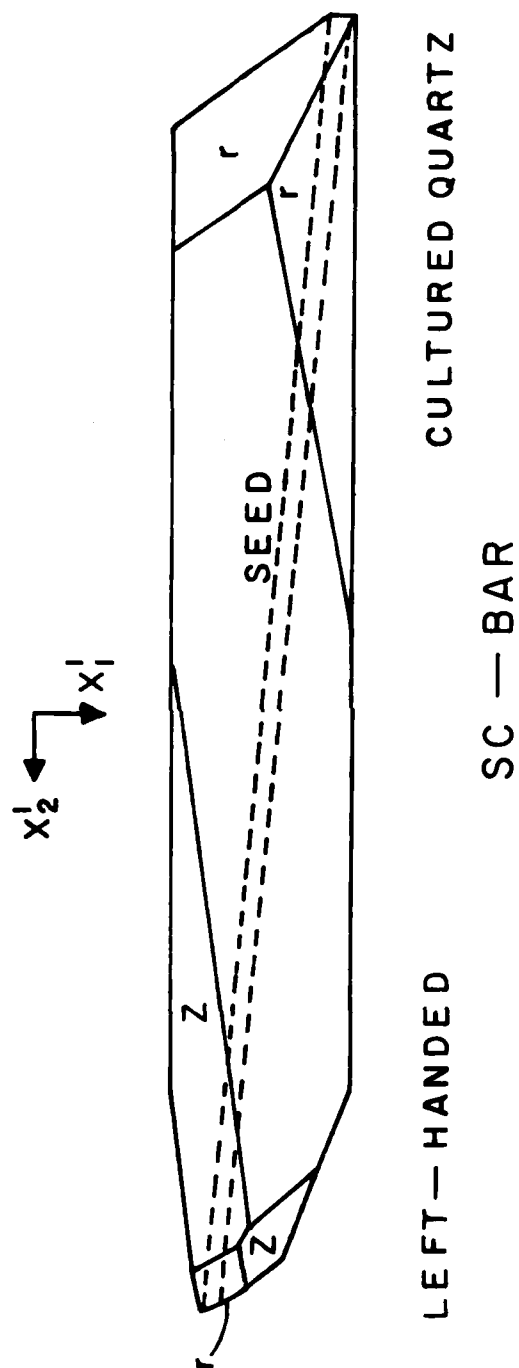


Figure 47. Line drawing of Figure 35.

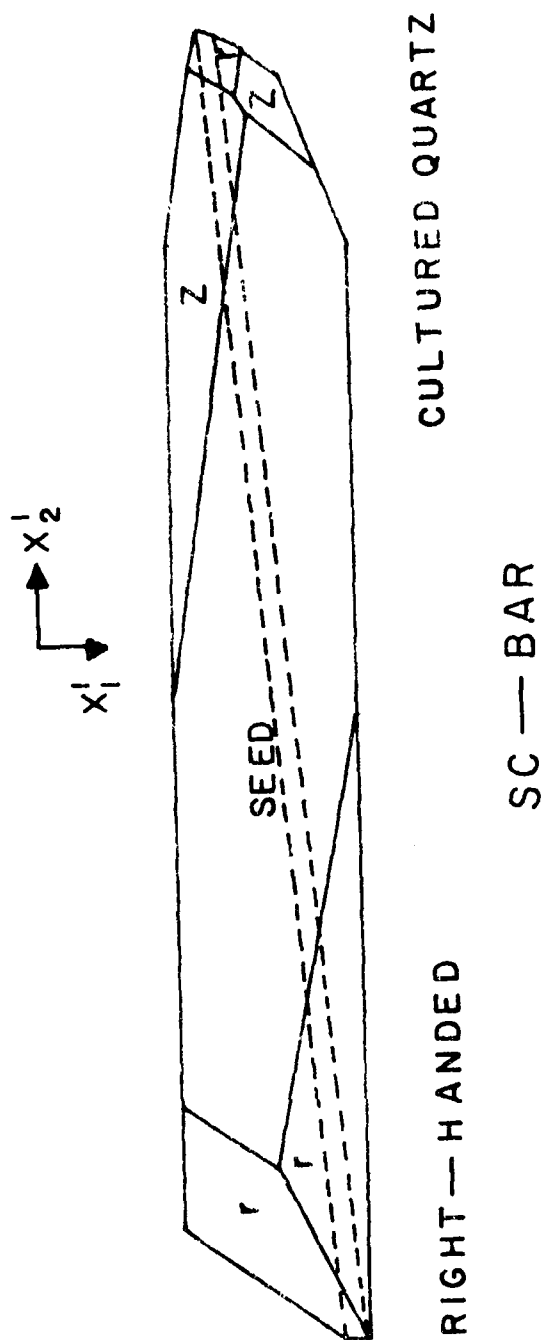
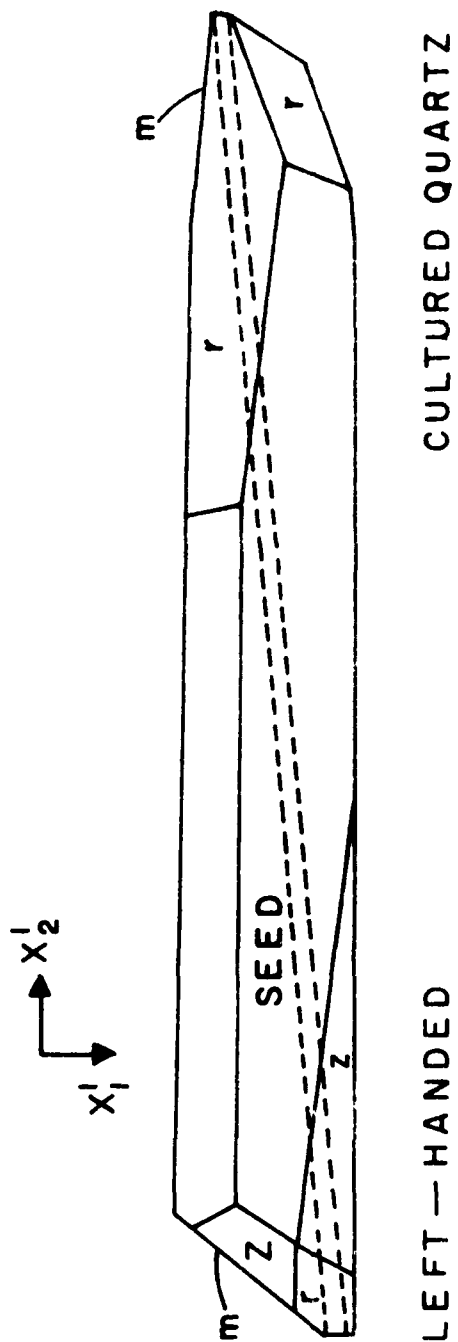


Figure 48. Line drawing of Figure 36.



SC - BAR

CULTURED QUARTZ

LEFT-HANDED

Figure 49. Line drawing of Figure 37.

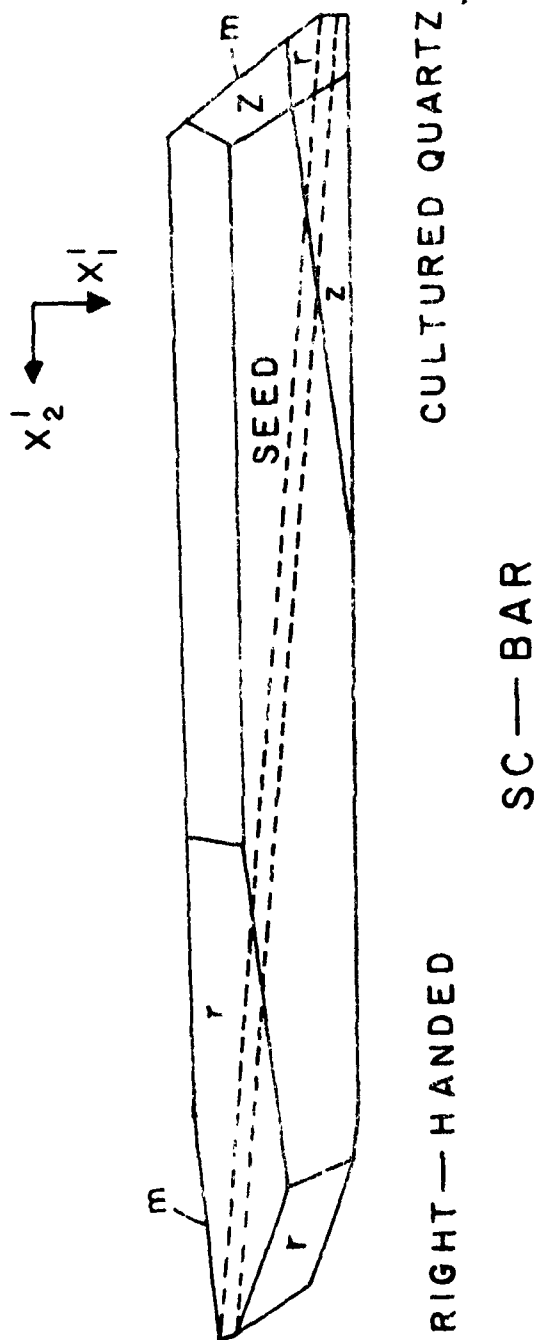
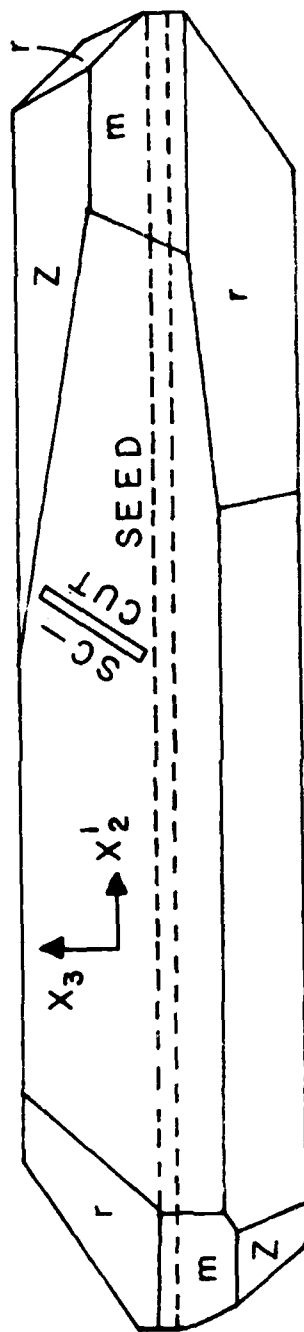


Figure 50. Line drawing of Figure 38.

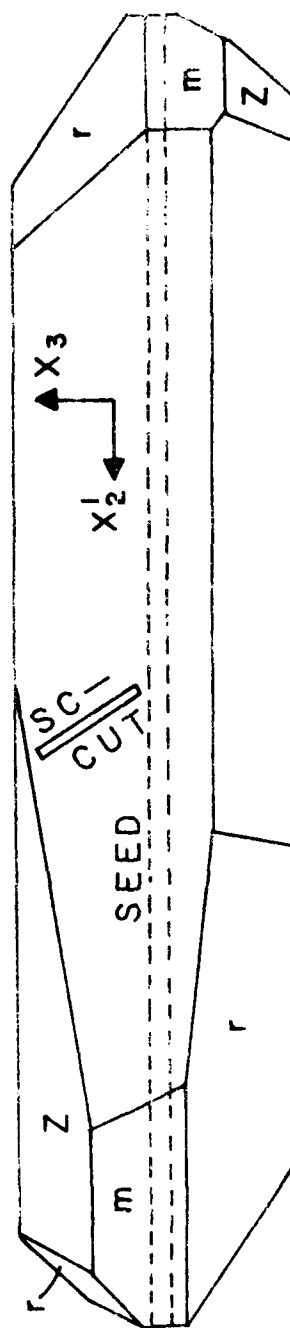


CULTURED QUARTZ

SC — BAR

LEFT — HANDED

Figure 51. Line drawing of Figure 39.

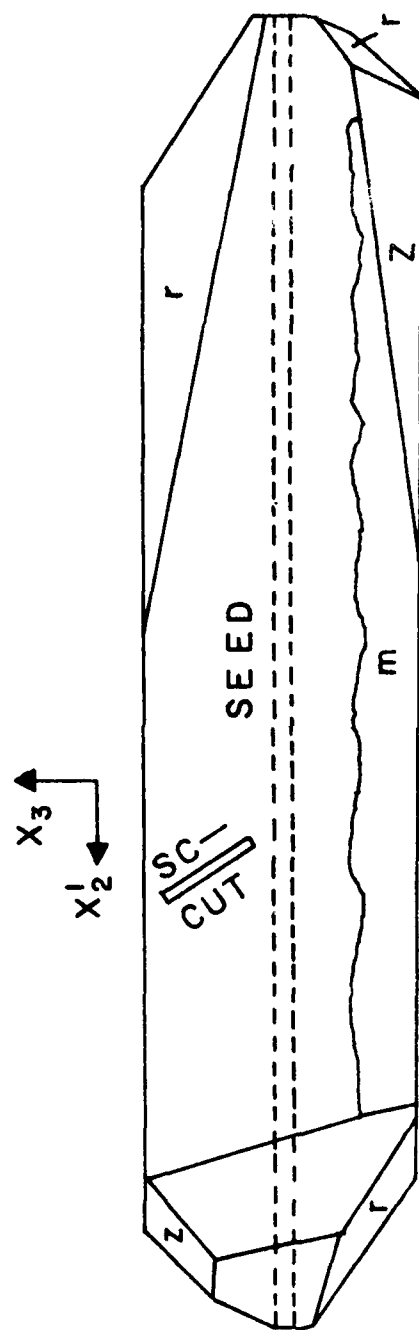


CULTURED QUARTZ

SC — BAR

RIGHT — HANDED

Figure 52. Line drawing of Figure 40.



LEFT - HANDED

SC - BAR

Figure 53. Line drawing of Figure 41.

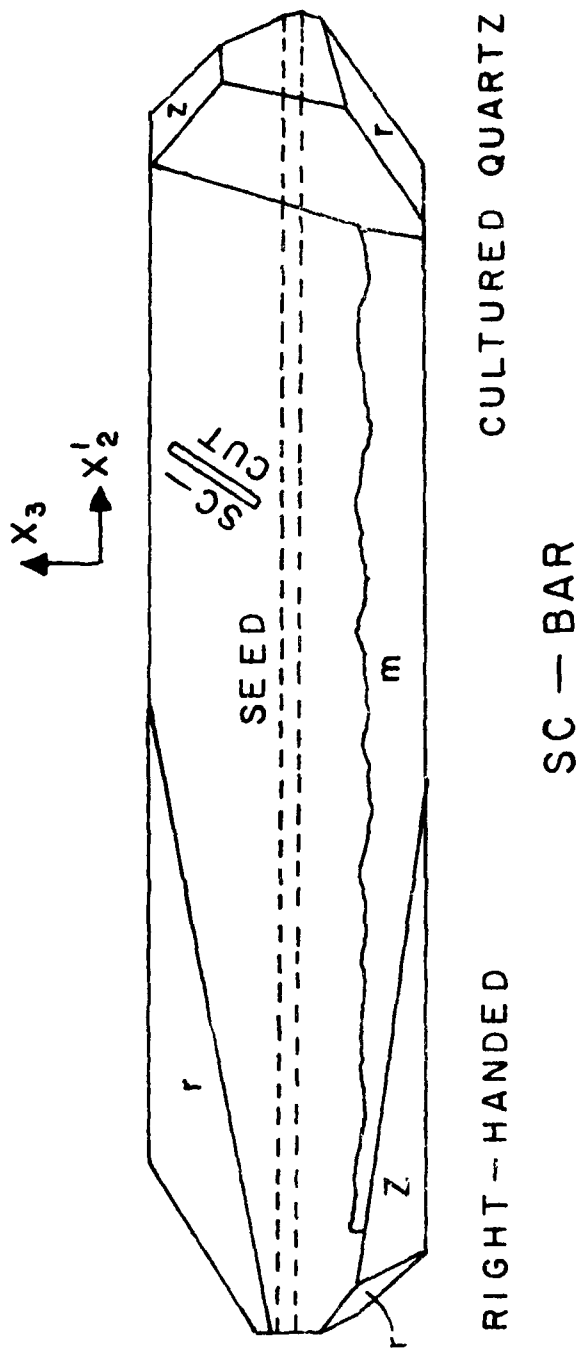
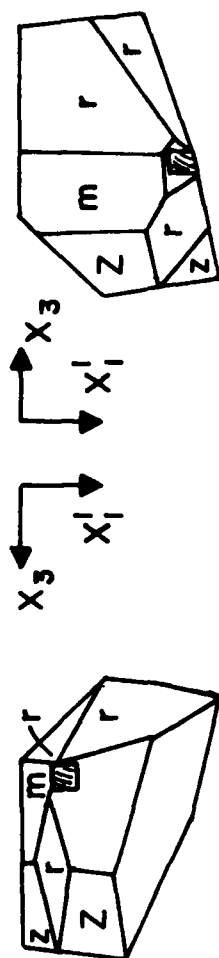
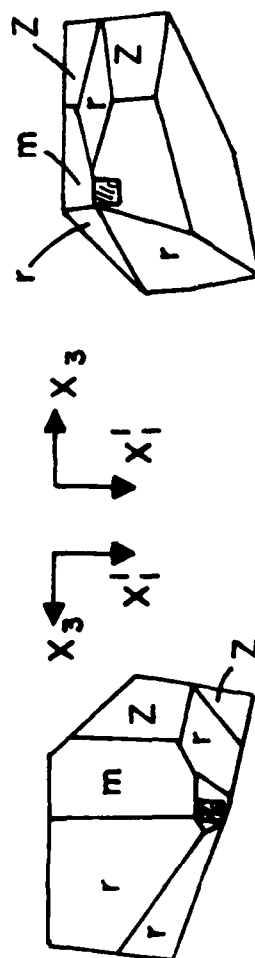


Figure 54. Line drawing of Figure 42.



RIGHT - HANDED



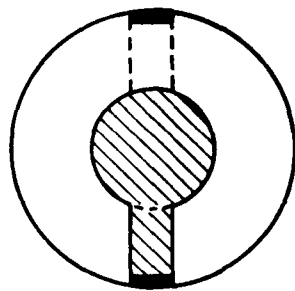
LEFT - HANDED

# SC - BAR CULTURED QUARTZ

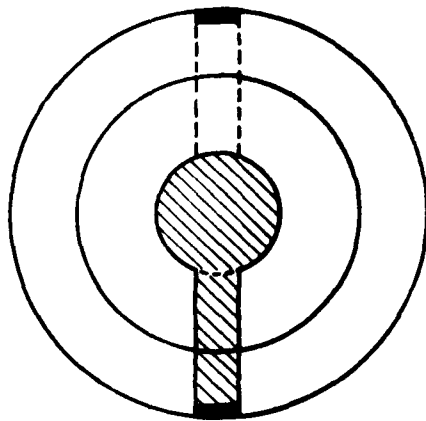
Figure 55. Line drawings of quartz Y-bar end faces.

# CRYSTAL RESONATORS

CONVENTIONAL



RING - SUPPORTED



OUT - OF - PLANE ACCELERATION



BOUNDARY CONDITIONS AT EDGES

SIMPLY SUPPORTED:

- (a) EDGE FORCES; ZERO DISPLACEMENTS
- (b) NO EDGE TORQUES; NONZERO SLOPES

DOUBLE CANTILEVER:

- (a) EDGE FORCES; ZERO DISPLACEMENTS
- (b) EDGE TORQUES; ZERO SLOPES

Figure 56. Ring-supported and conventional resonators.

periphery as described at the bottom of Figure 56. Frequency shift is proportional to deformation at the plate center, which is less for the ring-supported than the conventional resonator. When the acceleration is in the plane of the plate, one cannot make any a priori statements concerning the magnitude of the effect, except that it will depend on the azimuth angle of the acceleration field. The ring-supported resonator may be fabricated of any cut. The increased insensitivity of the SC cut over the AT, coupled with use of this structure may provide sufficient acceleration immunity in certain applications, so that resonators of this type can be used individually. Beyond this, paired enantiomorphs, either discrete or stacked may be used. The inverted mesa structure<sup>92,109,110</sup> formed in the central region of the plate need not be plano-plano. Either plano-convex or bi-convex forms are desirable alternatives:<sup>111,112</sup>

#### EQUIVALENT NETWORKS

The usual equivalent circuits used for crystals are inappropriate here because they do not take into account the piezoelectric polarities explicitly. Figure 57 shows the analog equivalent network<sup>63</sup> of a crystal wherein a single mode is piezoelectrically driven. The placement of the piezo-transformer dots and the coordinate axes identify the network as representing a right-handed crystal. The corresponding network for a left-handed crystal is given in Figure 58.

In Figure 59, the crystals of Figures 57 and 58 (schematized as boxes), are shown on either side of the central mirror plane of symmetry. The network representation of the reversal of the crystal axes by rotation of one of the plates about the thickness axis is depicted in Figure 60. Attachment of the crystals may now be made to realize either the discrete or the stacked configuration. If the discrete configuration is to be realized, then the following ports are shorted to indicate traction-free mechanical boundary conditions: CD, EF, IJ, and KL. Ports AB and GH are then connected electrically in series or parallel as indicated in the discussion of Figures 27 and 28.

Realization of the stacked configuration requires, in Figure 60, the direct connection of mechanical ports CD and IJ to each other, and shorting of ports EF and KL. The electrical ports are treated as above.

The case of a stacked, doubly rotated pair of plates is shown in Figure 61. Here all three thickness modes are excited in each plate. The rotation of one plate about the thickness axis required for acceleration compensation is represented by the mechanical transformers in the center if we select minus one as the turns ratio. When two of the thickness modes can be neglected compared to the third, then the resulting network appears as in Figure 62 with the minus one ratio chosen. The inductances labeled L are equivalents of electrode mass.<sup>54</sup> Connection of terminals A to D and B to C in Figure 62 produces the parallel connection seen on the left side of Figure 28. Figure 63 shows the equivalent circuit for the situation given in Figure 62, including the presence of the two additional, piezoelectrically undriven, thickness modes.

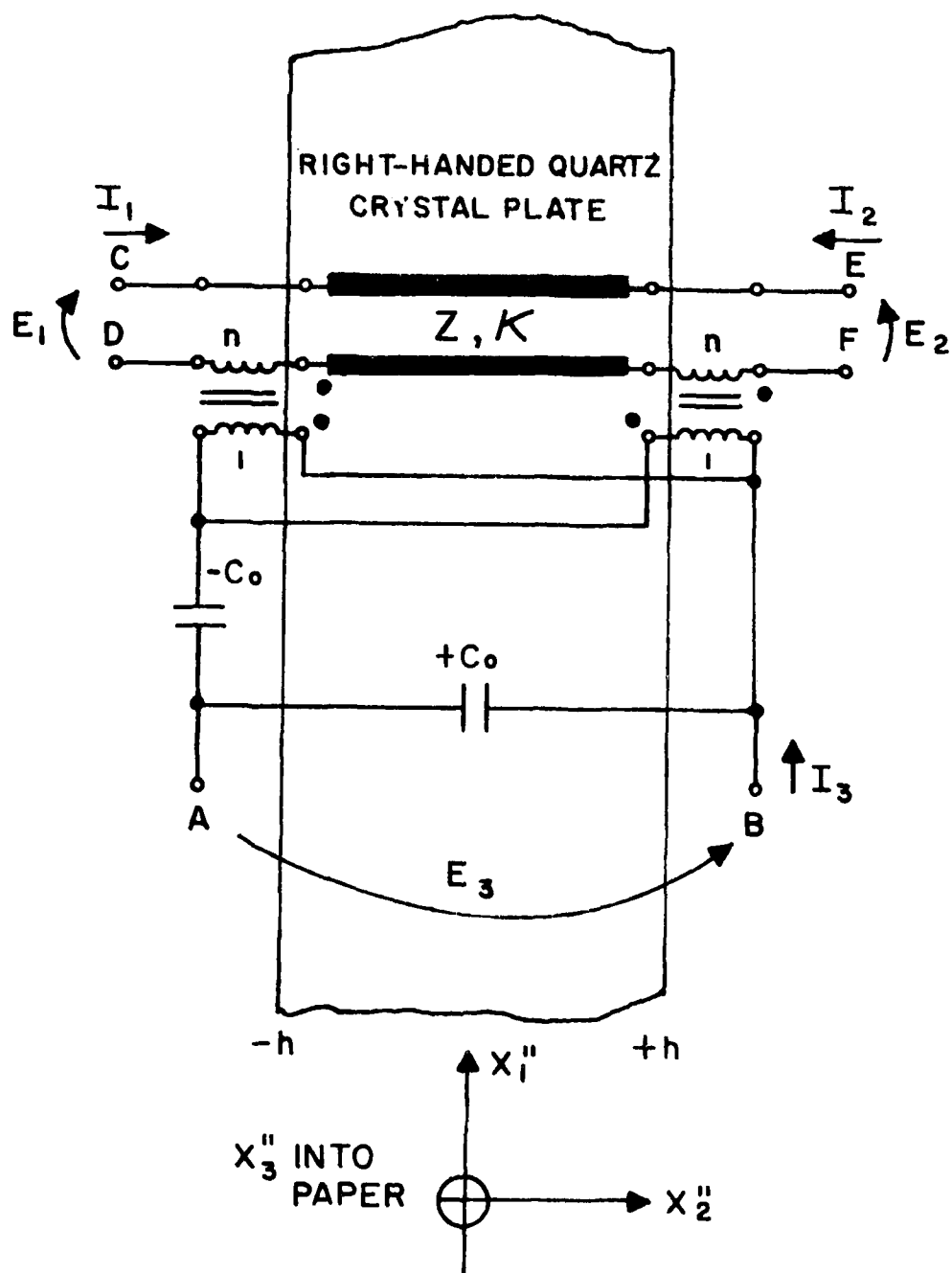


Figure 57. Network for right-handed quartz plate.

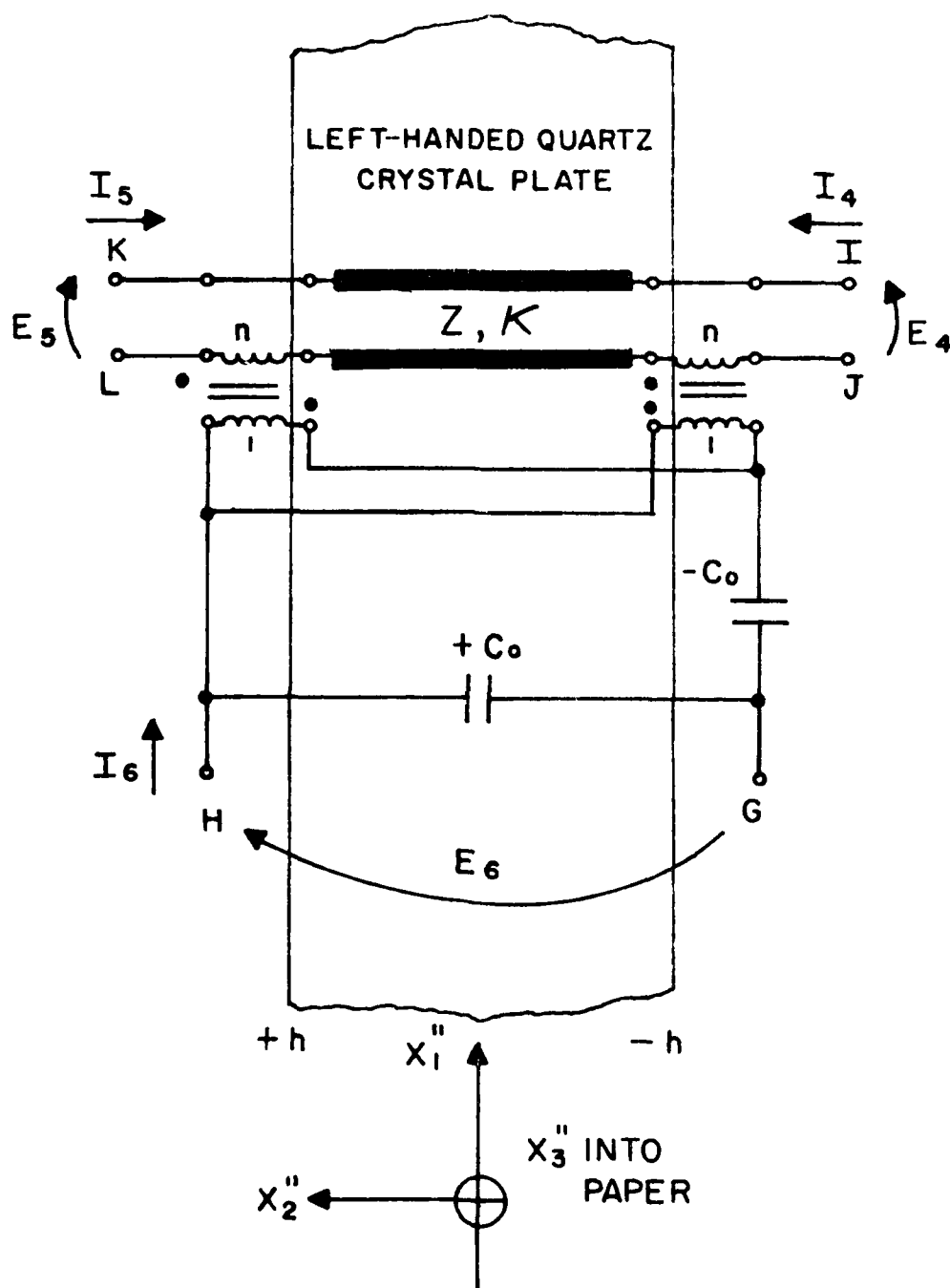


Figure 58. Network for left-handed quartz plate.

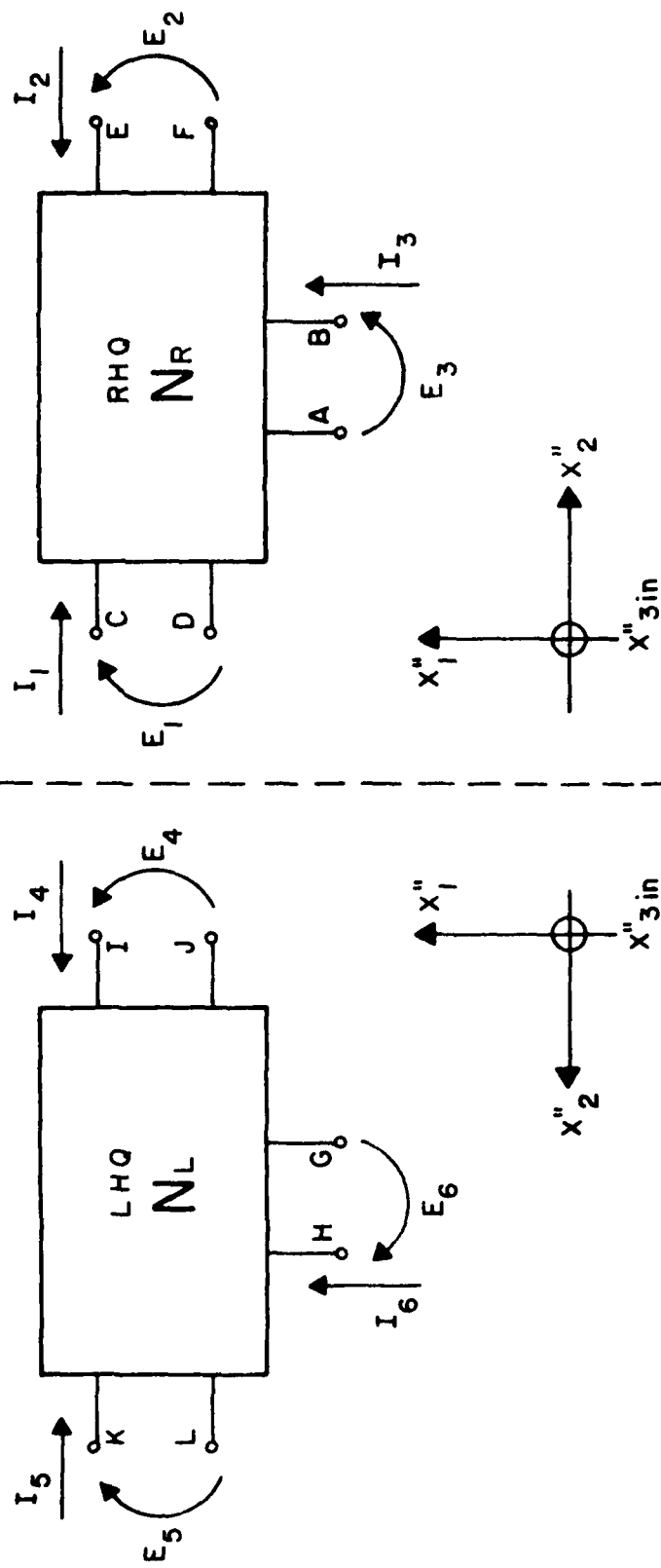


Figure 59. Networks of Figures 57 and 58 regarded as mirror pair.

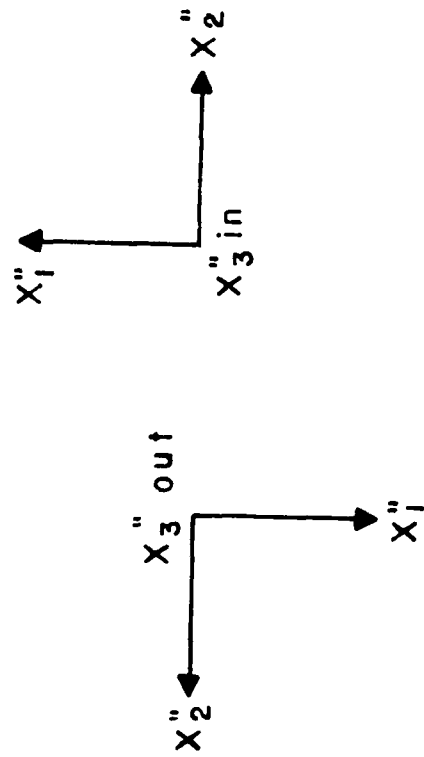
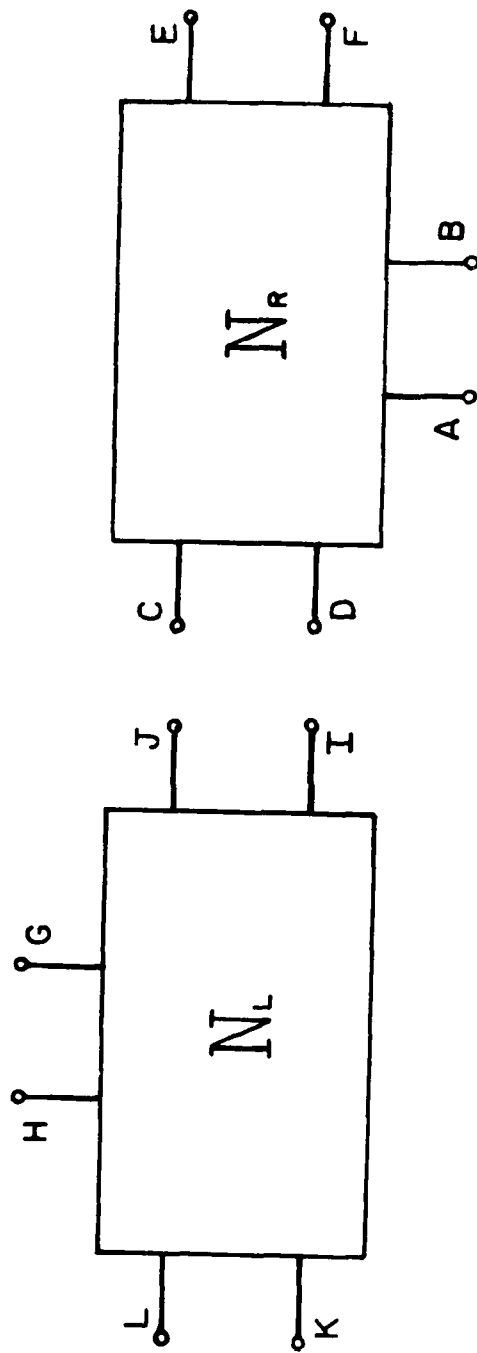


Figure 60. Networks of Figure 59 arranged with axes antiparallel.

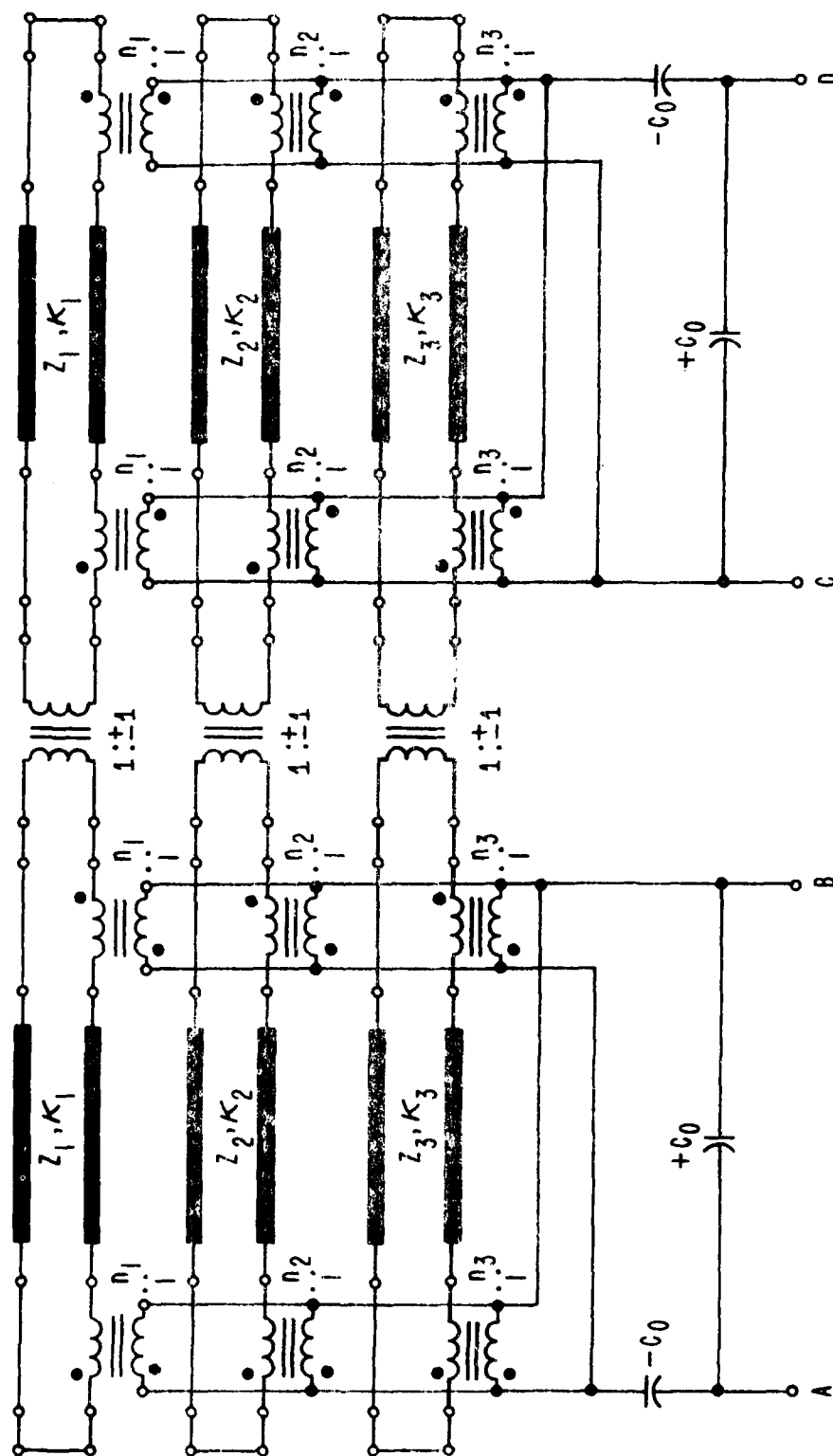


Figure 61. Network of crystal stack with three modes driven.

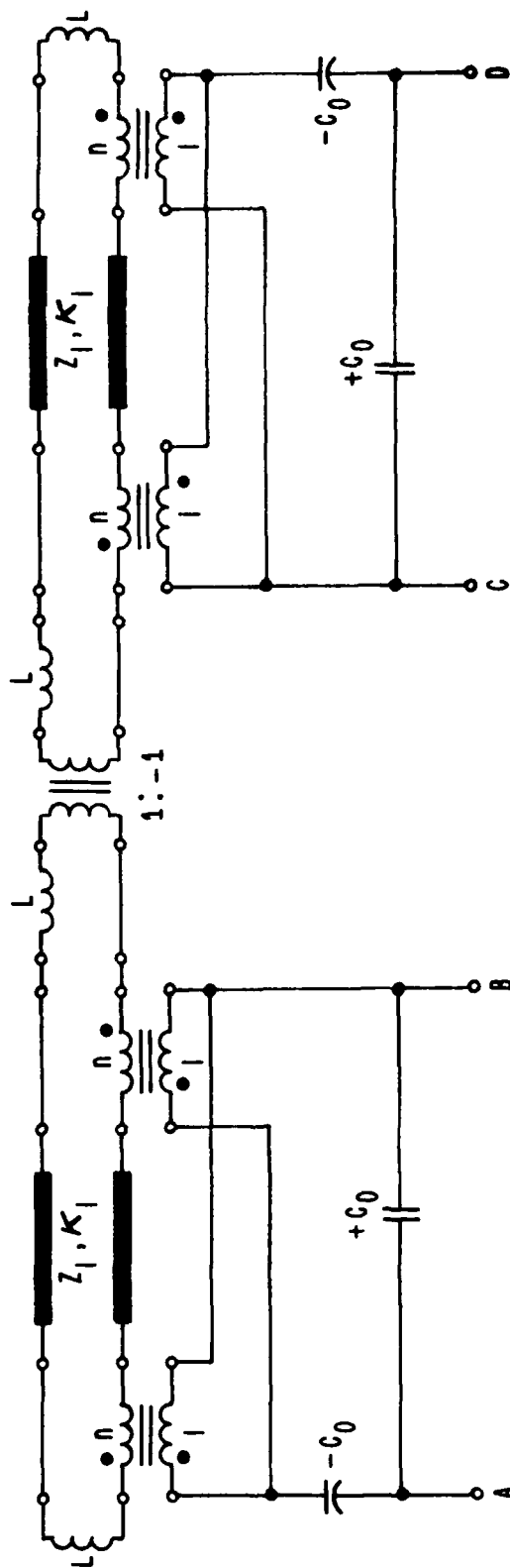


Figure 62. Network of crystal stack with one mode driven.

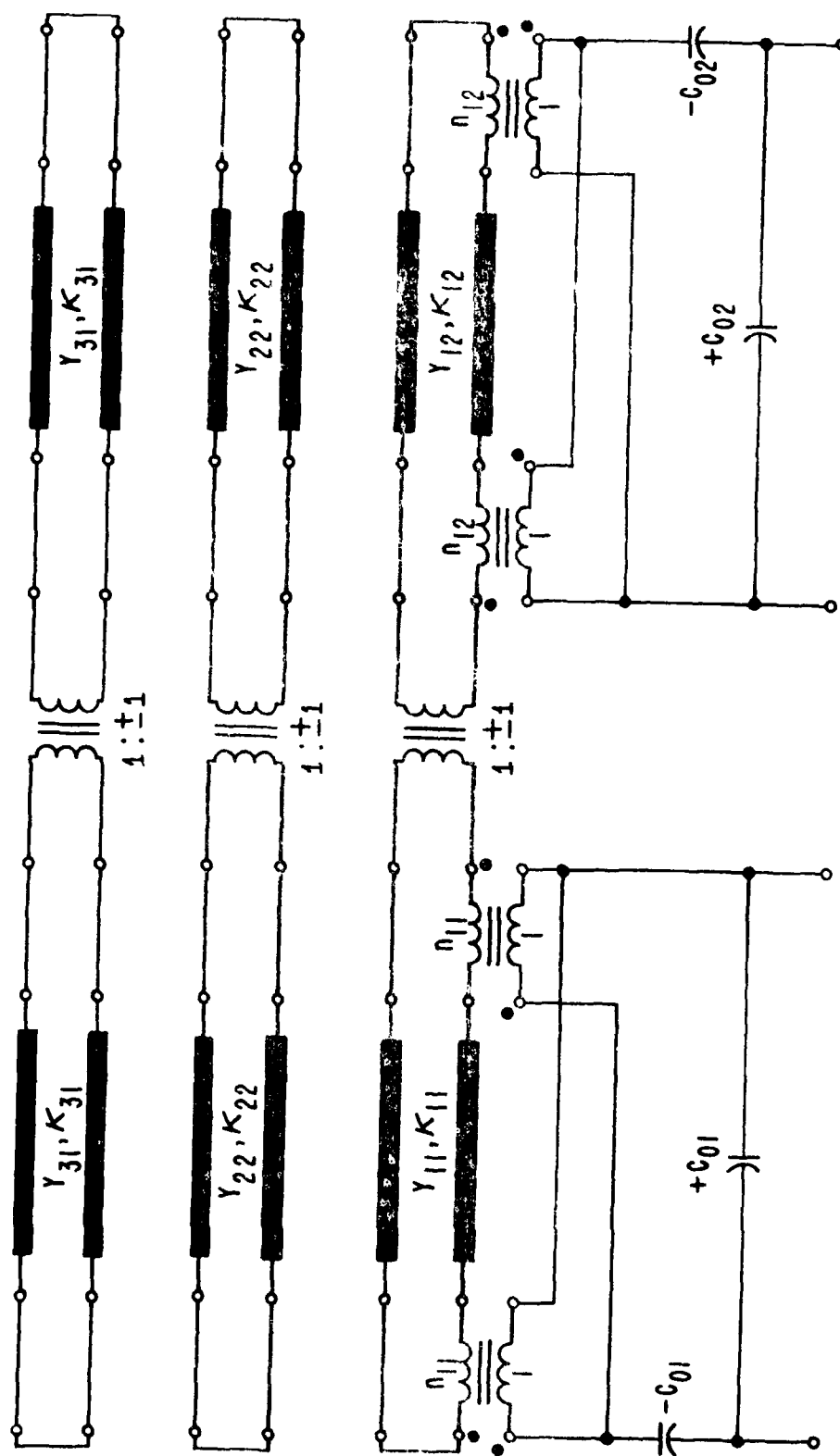


Figure 63. Three mode network with one mode driven.

In order for the networks shown to simulate the effects of an acceleration field, the individual parameters must be made functions of the acceleration; this can be done without any great difficulty. In the configurations where compensation takes place, the net frequency deviation will be zero provided the resonators forming the composite are identical in design, in reference frequency and in mounting. The compensation described in this report arises from geometrical considerations regarding the crystals; it is assumed that the boundary conditions are likewise identical; any departure from symmetry in this regard could be expected to produce deteriorated performance. Any misorientations due to manufacturing deviations resulting in slight relative rotations of the plate about the common thickness (Y) direction will couple all three thickness modes together via a mechanical interface transformer<sup>63</sup> with turns ratios that depart from zero as  $\sin \psi$  where  $\psi$  is the small angular error, and from one as  $\cos \psi$ .

## CONCLUSION

The balanced enantiomorphous structures described in this report possess the advantage of admitting considerable variety in design and use. Some principal features permitted are:

- Compensation for arbitrary acceleration directions
- Discrete or stacked resonator configurations
- Singly or doubly rotated cuts
- Special mounting systems
  - \* BVA design <sup>53,55,113,114</sup>
  - \* Rhomboid resonators <sup>31</sup>
  - \* Ring- supported resonators <sup>107</sup>
- Any crystal in an enantiomorphous class
- Plano-plano, plano-convex, or bi-convex plates
- Any mode type for which reversal of the acceleration field is found to reverse the frequency shift in a single resonator
  - \* Thickness bulk acoustic wave (BAW)
  - \* Contour BAW
  - \* Flexure BAW
  - \* Surface acoustic wave (SAW)
  - \* Shallow BAW (SBAW)<sup>115-117</sup> or surface-skimming bulk wave (SSBW); see Figure 64
  - \* Composite resonator<sup>91</sup>; see Figure 65

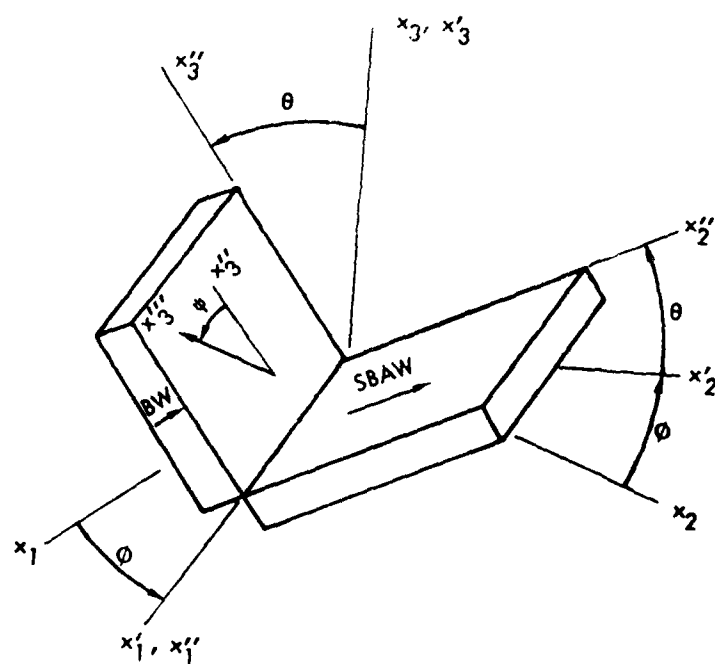


Figure 64. Bulk wave (BW) and shallow bulk acoustic wave (SBAW) plates.

THIN-FILM LAYER OF HIGH-COUPLING  
PIEZOELECTRIC CRYSTAL DRIVES THE  
COMPOSITE STRUCTURE.

ELECTRODES

QUARTZ  
SUBSTRATE

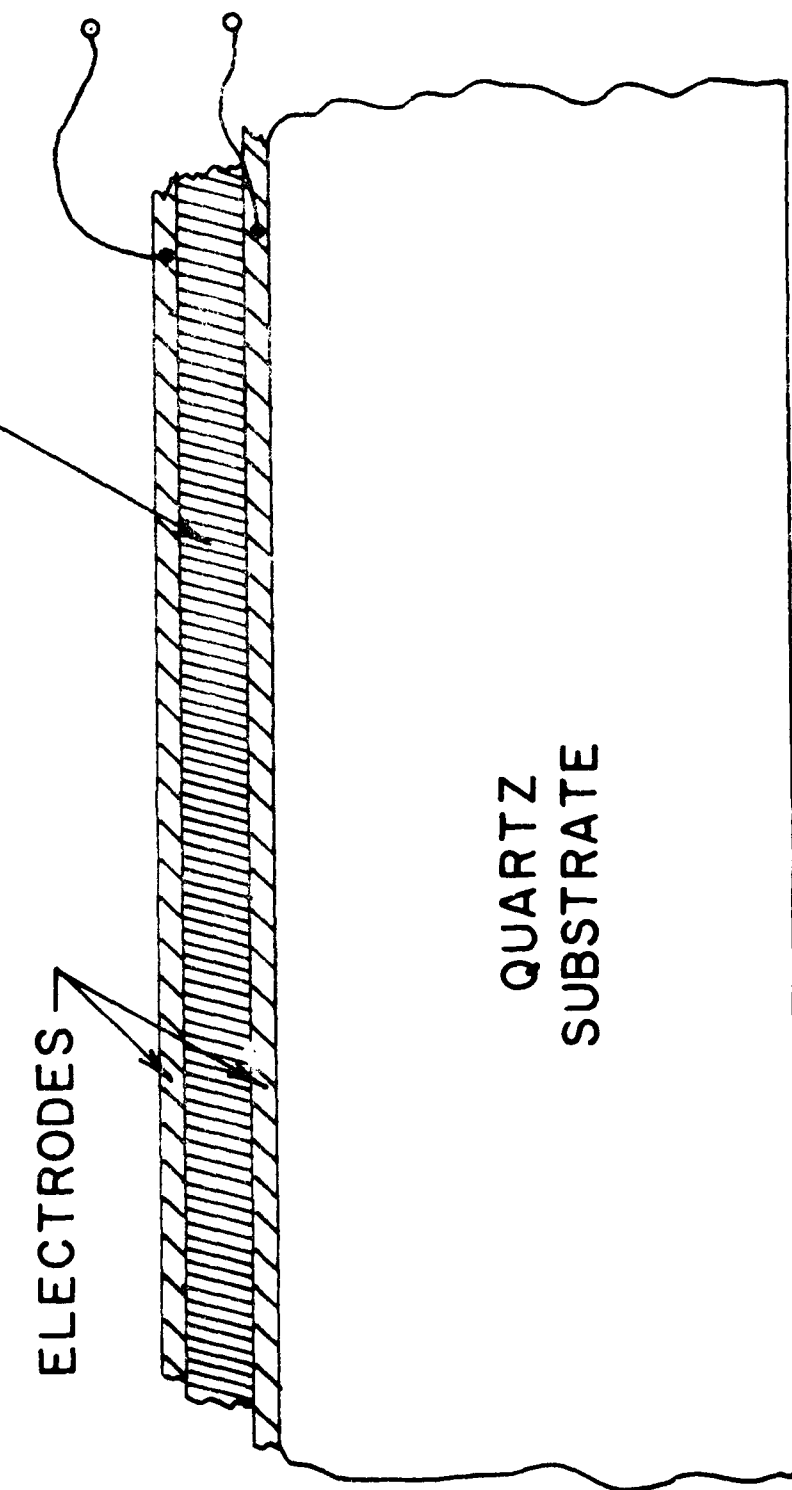


Figure 65. Composite resonator structure.

- Lateral<sup>118,119</sup> (LETM) as well as thickness excitation (TETM)
- Series or parallel electrical connection
- Combinations of the foregoing

For example, a possible combination consists of two ring-supported resonators, each having a plano-convex contour in the inverted mesa portion, stacked together with ring structures abutting.

Disadvantages of these combinations are the following:

- Difficulty of bonding or joining plates in stacked structures; (but see Reference 93)
- Edge mountings of circular resonators are sensitive to small orientational errors<sup>46,49</sup>
- Stacking misorientation errors couple plate modes<sup>63,119</sup>

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